THE EUROPEAN SCHOOL ON MAGNETISM

MAGNETIC SENSORS

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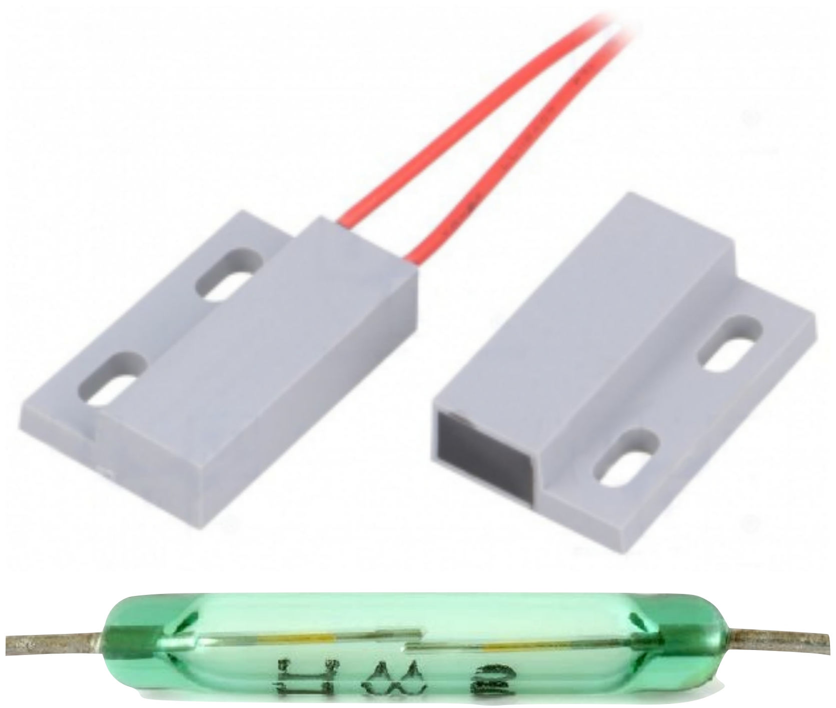
1. Introduction

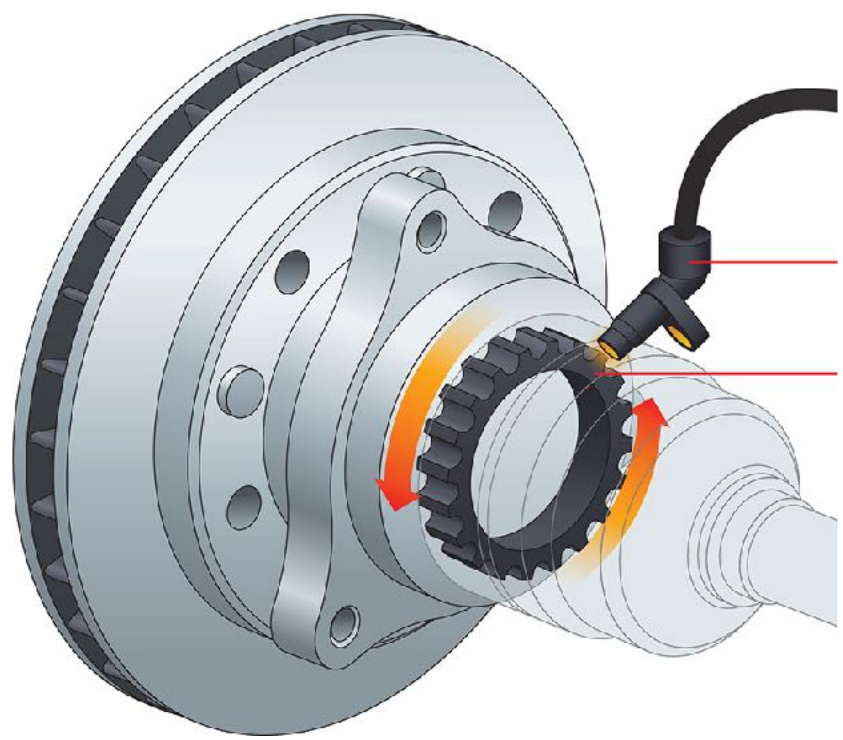
Magnetic sensors: *what and what not*

Very general definition:

A magnetic sensor is a measuring or detection device that makes use of magnetic phenomena.



Reed relay



Anti-lock Braking System (ABS)

Magnetoencephalography

1. Introduction. Magnetic sensors: *what and what not*

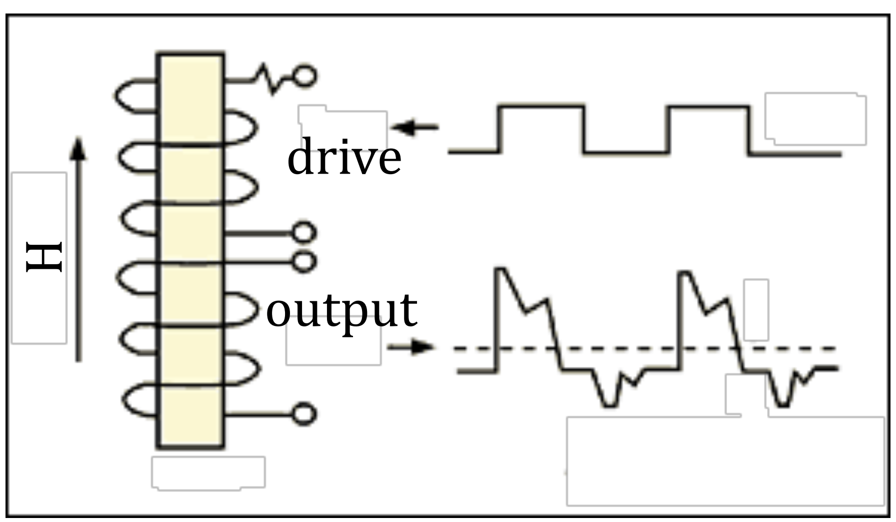
Selective review:

We will not talk about every kind of magnetic sensors.

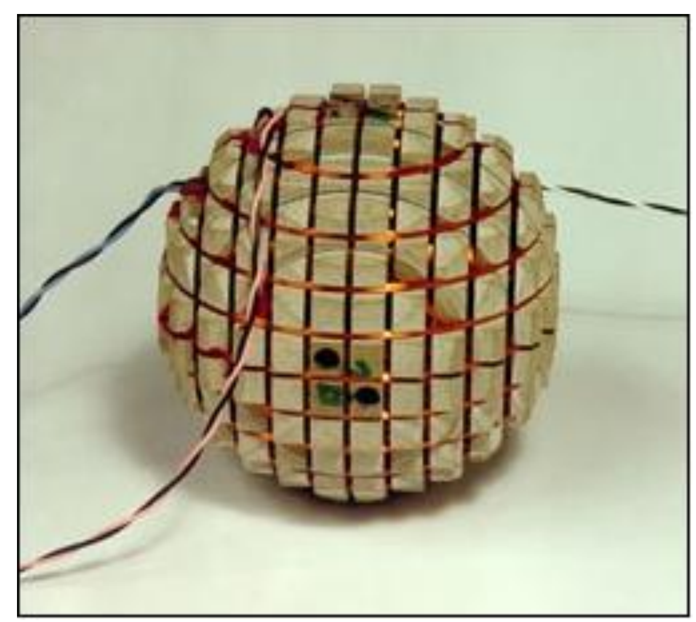
Only most relevant technologies will be presented, illustrated with selected examples.

No fine details:

The basic operating principle will be examined, but not the technological complexity of a working device.



fluxgate principle



fluxgate space magnetometer

1. Introduction. Magnetic sensors: *what and what not*

Focused description:

Sensor technology combines several disciplines: *electronics, signal conditioning, instrumentation, metrology, etc*…

We will focus on the *magnetic* principles.

In particular, we will not directly deal with very important aspects and characteristics of sensors, such as

calibration,

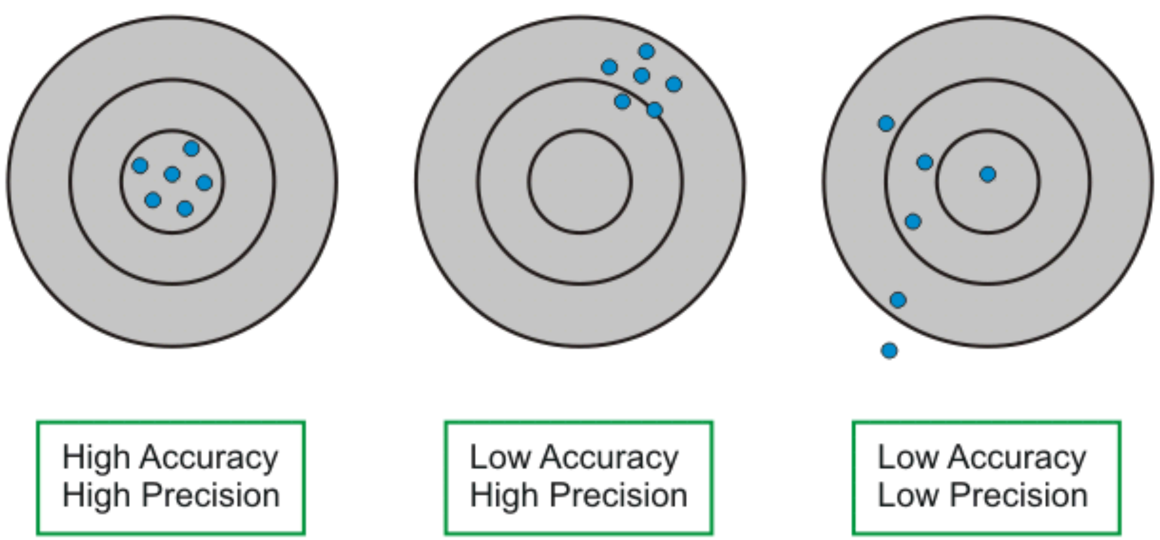
accuracy,

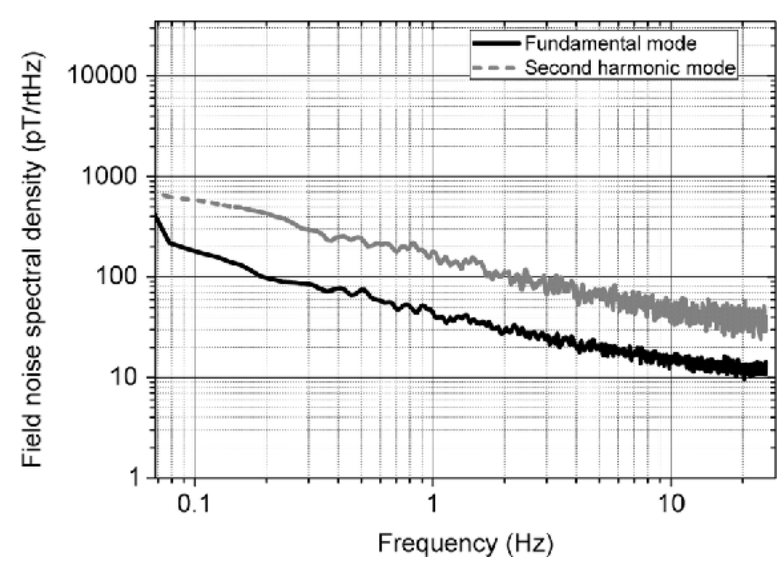
resolution,

precision,

noise,

…





Recommended reading:

C. W. de Silva, *Sensor systems: fundamentals and applications* (CRC press, 2017).

ISBN: 9781498716246

1. Introduction
Magnetic materials for sensors

Main requisites:

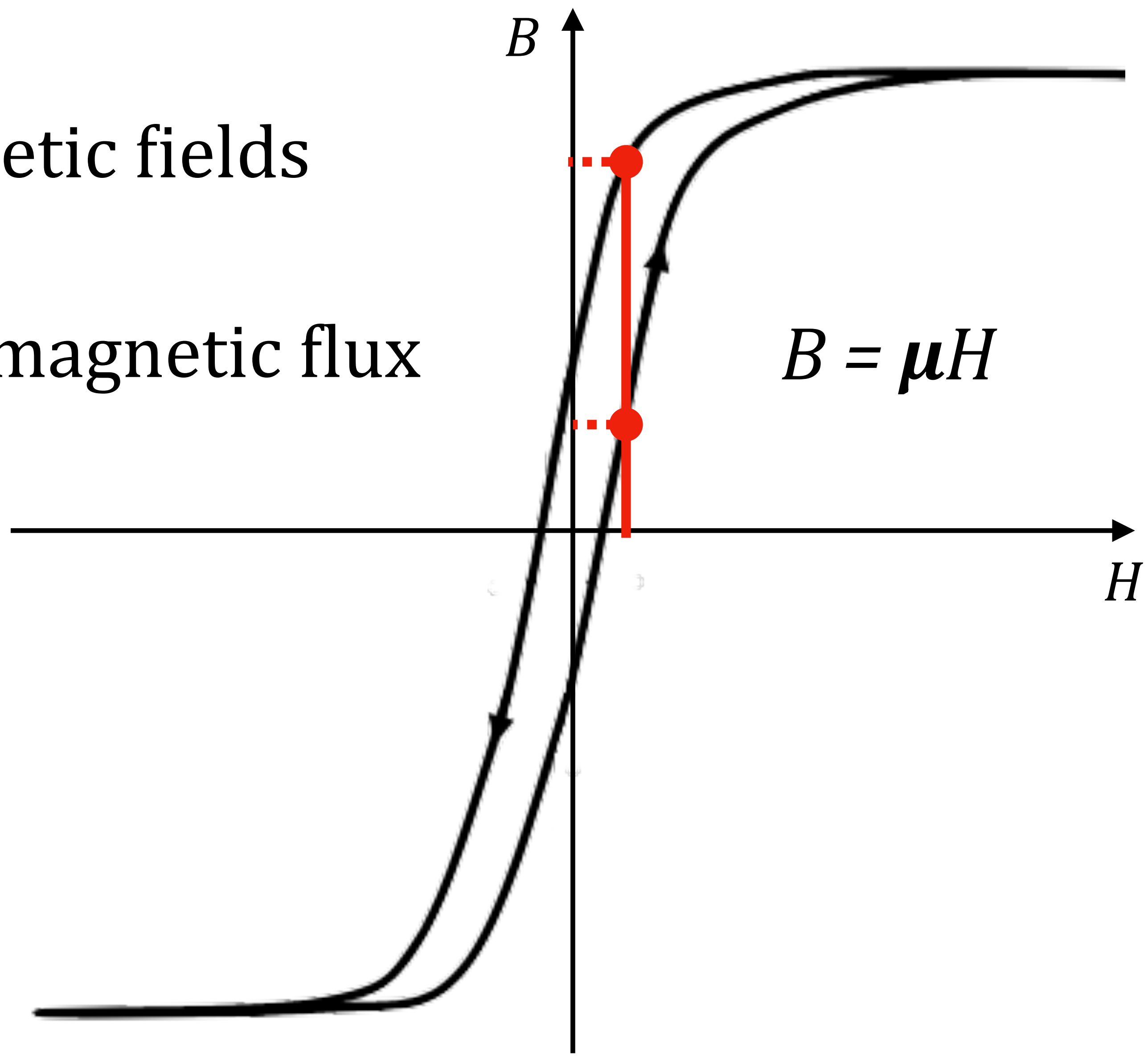
Large permeability

- high sensitivity to small magnetic fields
- intensify the field
- concentration and guiding of magnetic flux

Low magnetic hysteresis

- well defined magnetic state
- reduce losses

Soft magnetic materials



Other requisites:

Mechanical, thermal, … properties

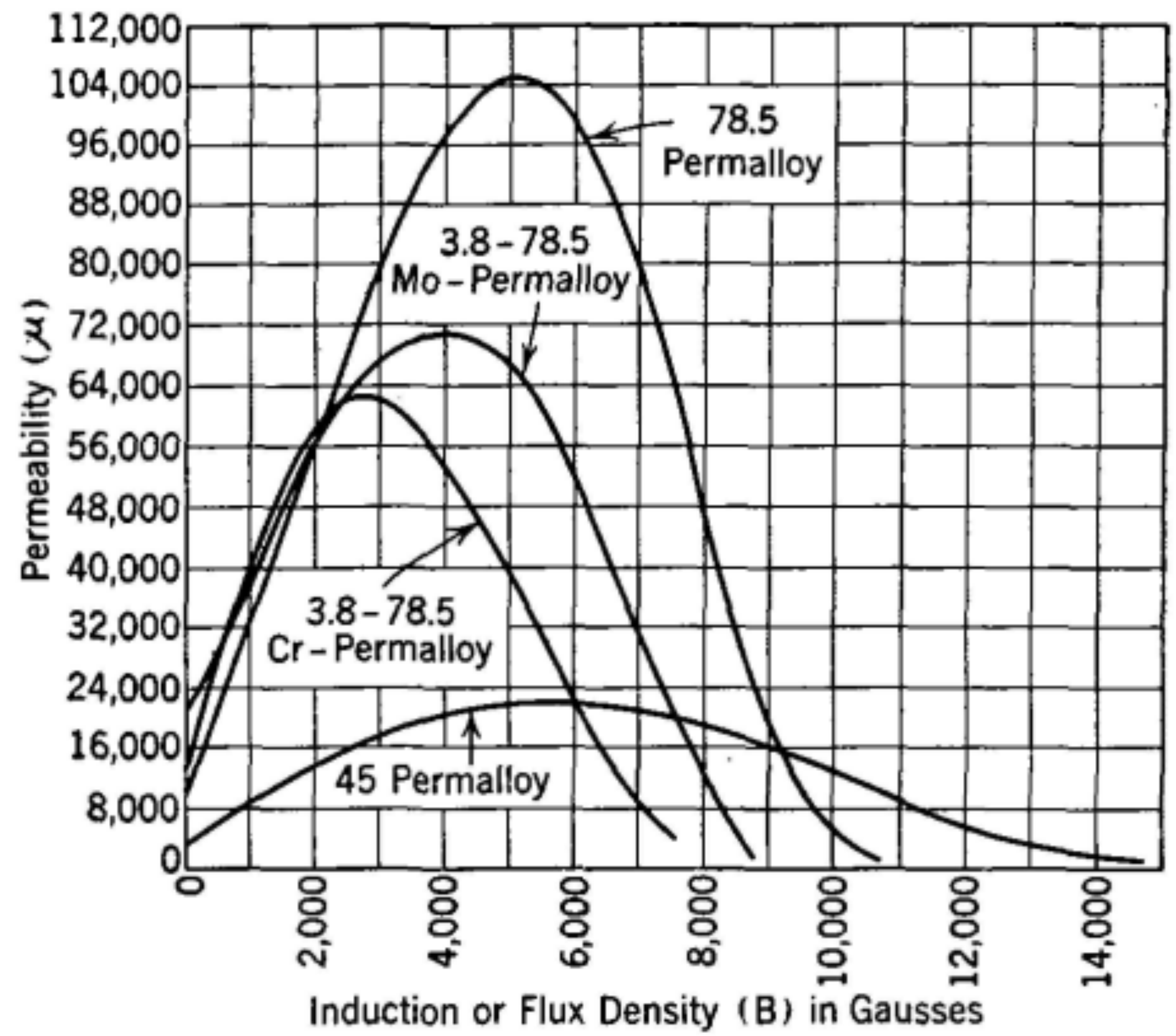
Availability, price, …

Fe-Ni alloys:

Permalloy ($Fe_{100-x}Ni_x$) presents very low crystalline anisotropy and magnetostriction.

With $x\sim 80$ at. %, $\mu > 10^5$.

$\mu_0 M_s \sim 1$ T.



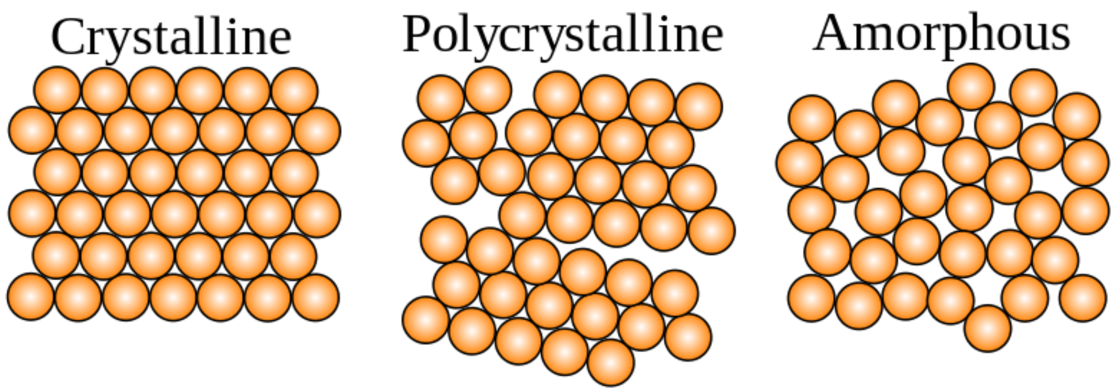
Other related materials:

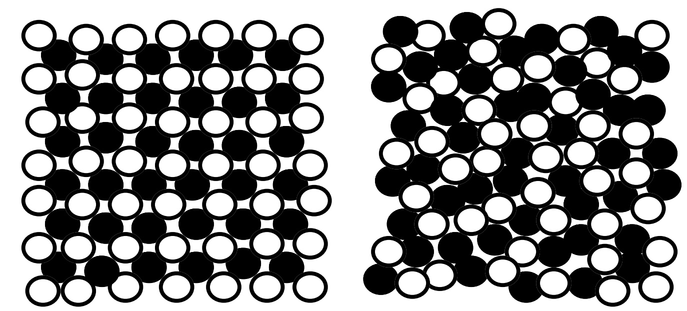
- Supermalloy (with Molybdenum)
- Mumetal (with Copper)

Extensive documentation on properties:
R. M. Bozorth, *Ferromagnetism* (IEEE press, 1991).
ISBN: 0-7803-1032-2

Amorphous alloys:

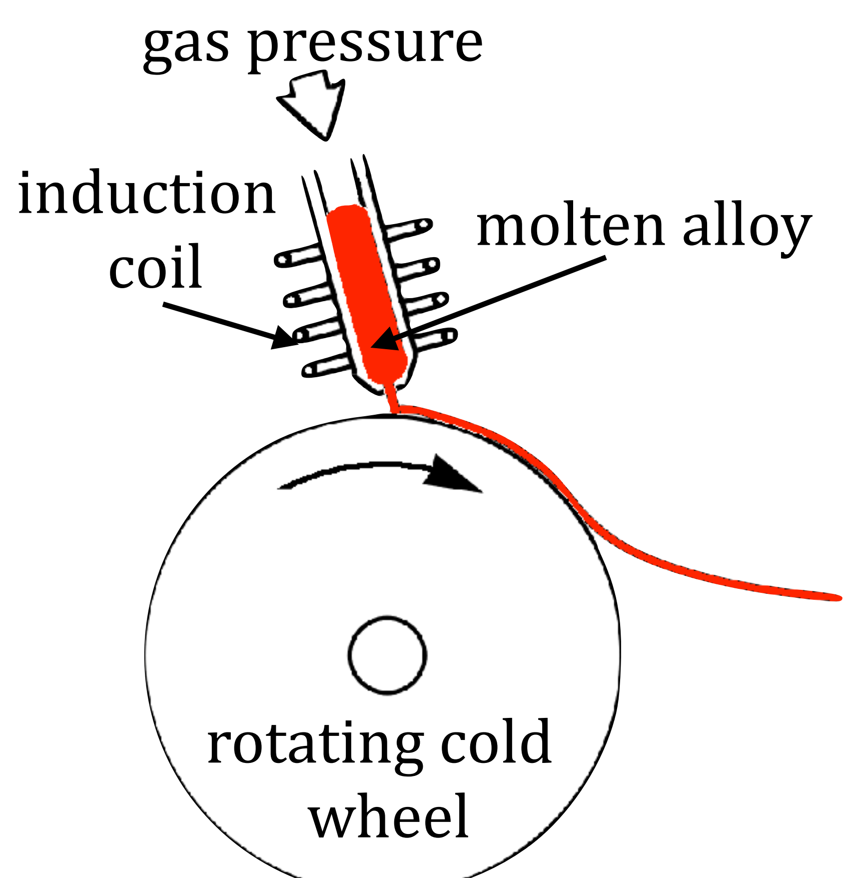
Amorphous materials lack crystalline order. The atomic configuration presents topological and chemical disorder (if alloys).

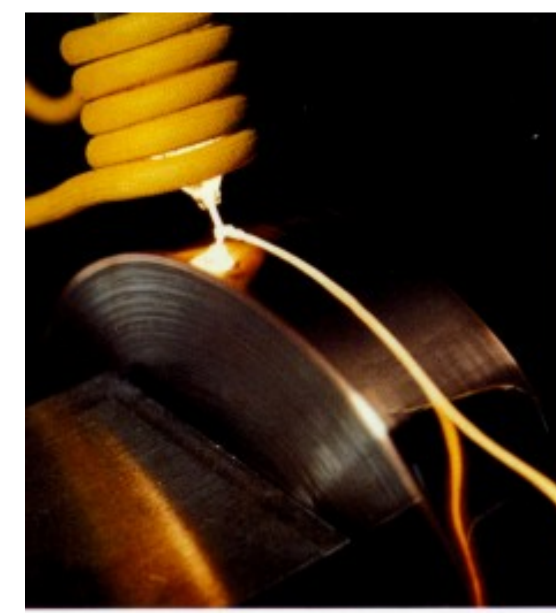




Amorphous ferromagnetic materials can be obtained by alloying Fe, Co, Ni (~80 at. %) with metalloids as B, P, Si, C, etc (~20 at.%) by rapid quenching from the melt (10^6 degrees per second).

Also called *metallic glasses.*





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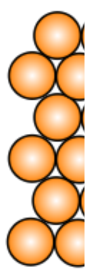

J. M. Silveyra *et al*, Science **362**, eaao0195 (2018).

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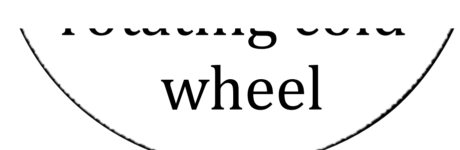


Also called *metallic glasses.*

The softness comes from

- lack of crystalline anisotropy
- no defects of grain boundaries for domain wall pinning.

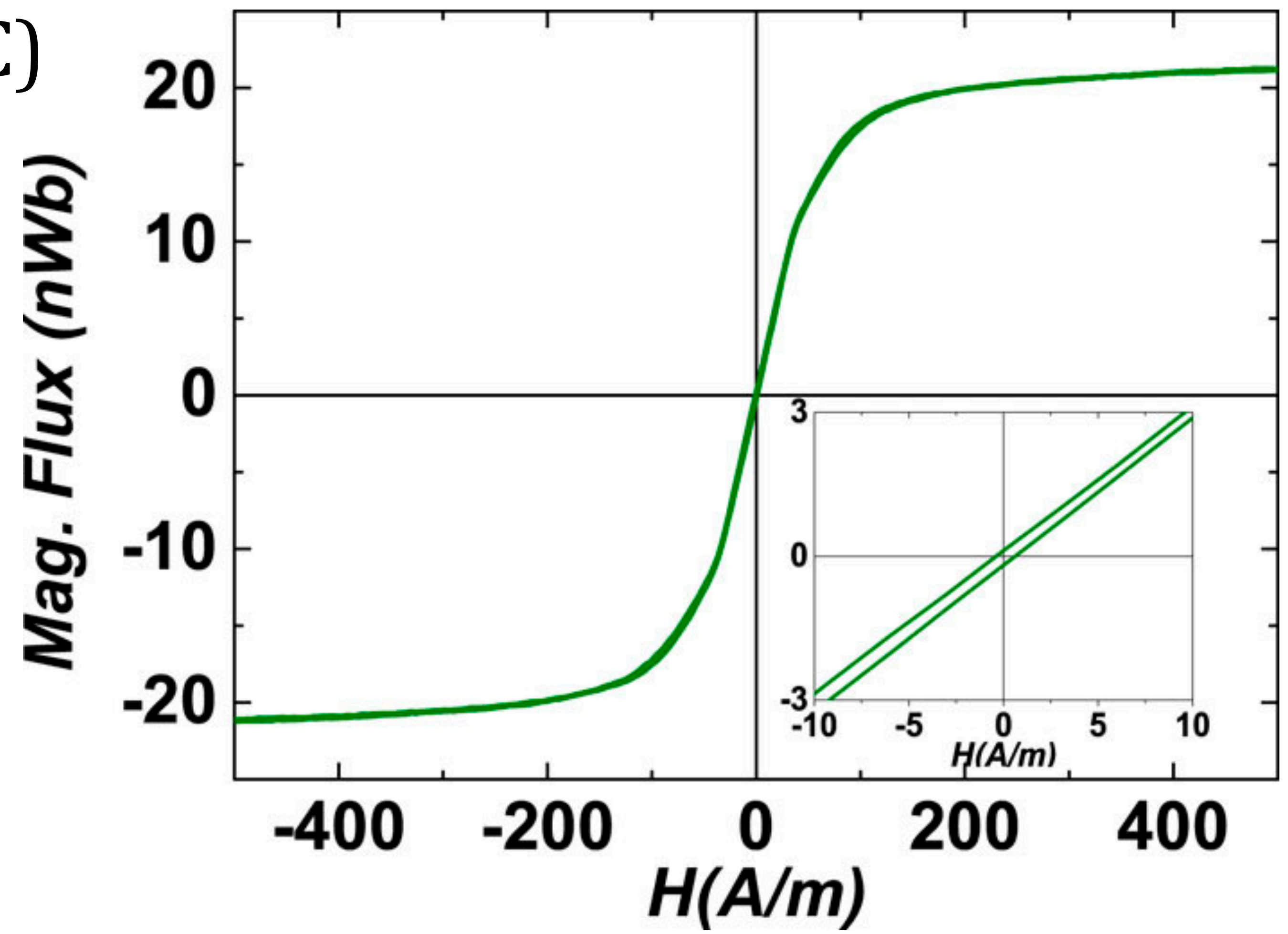
As an example:

$Fe_{40}Ni_{38}Mo_4B_{18}$ (Metglas 2628SC)

$\mu_{max} = 4 \times 10^5$.

$\mu_0 M_s = 0.88$ T.

Hysteresis loop of a Co-Fe-B amorphous ribbon



Ackland et al. AIP Advances 8, 056129 (2018)

F.E. Luborsky, *Amorphous ferromagnets*, in: *Handbook of Ferromagnetic Materials*, Vol. 1, Chapter 6. Elsevier (1980) pp. 451-529. ISBN 9780444853110

P. Hansen, *Magnetic amorphous alloys*, in: *Handbook of Magnetic Materials*, Chapter 4. Elsevier (1991) pp. 289-452.

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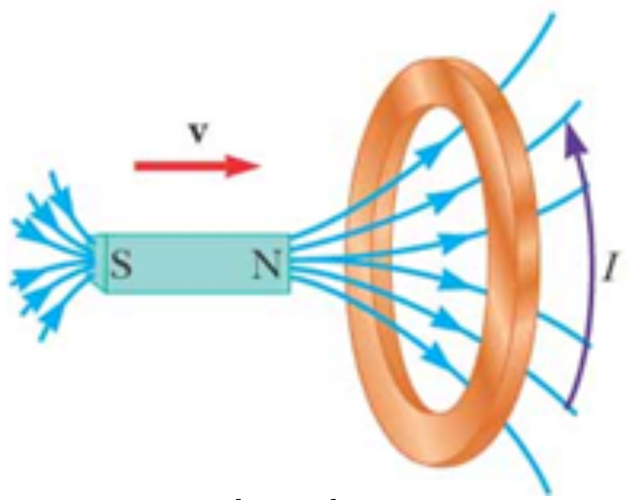
2. Sensing principles and examples
Inductive sensors

Basic underlaying principle: Faraday's induction law



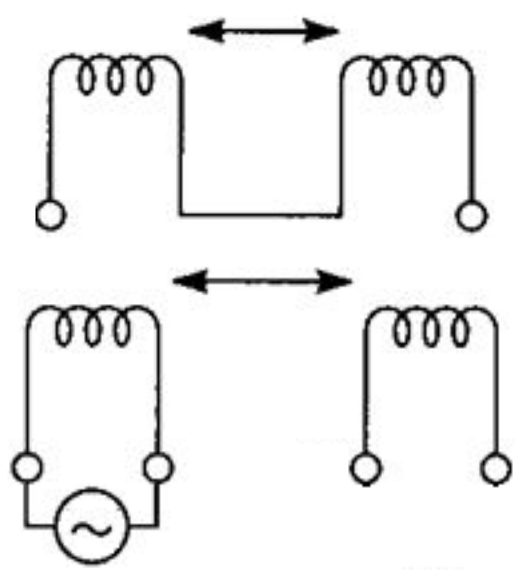
source: physicsabout.com

$$\varepsilon = -\frac{d\phi}{dt} \qquad \phi = \int_S \vec{B} \cdot d\vec{s}$$

Michael Faraday (1791- 1867)

Different configurations, based on:

- changes on self-inductance $\phi = LI$
- changes on mutual-inductance $\phi = MI$

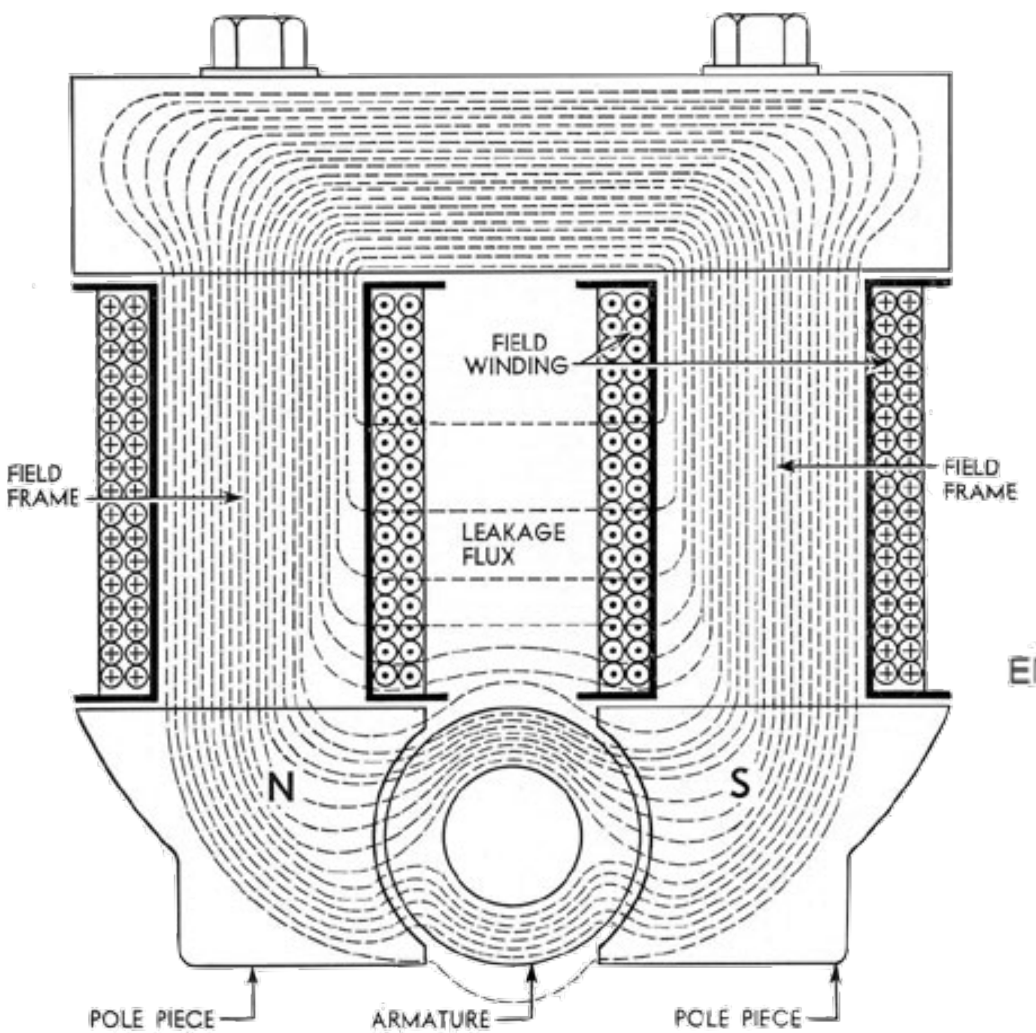


Magnetic circuits:

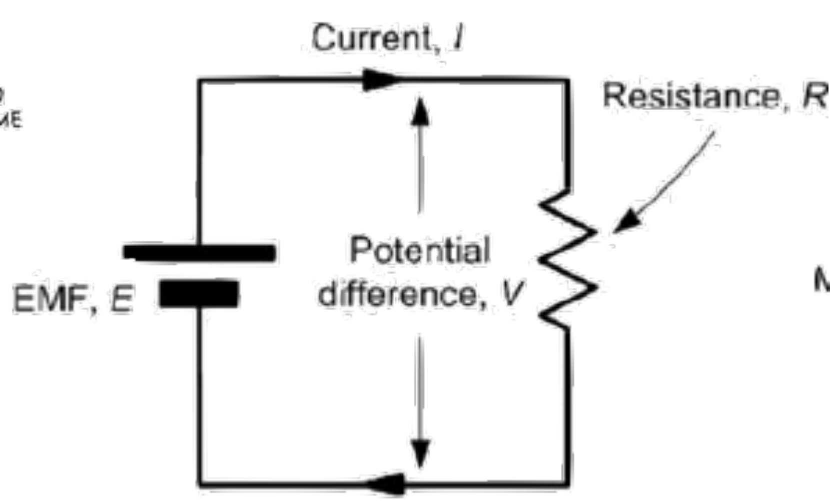
Magnetic materials *guide* and *concentrate* the magnetic field

The flux circulates through the path created by the high permeability magnetic materials.

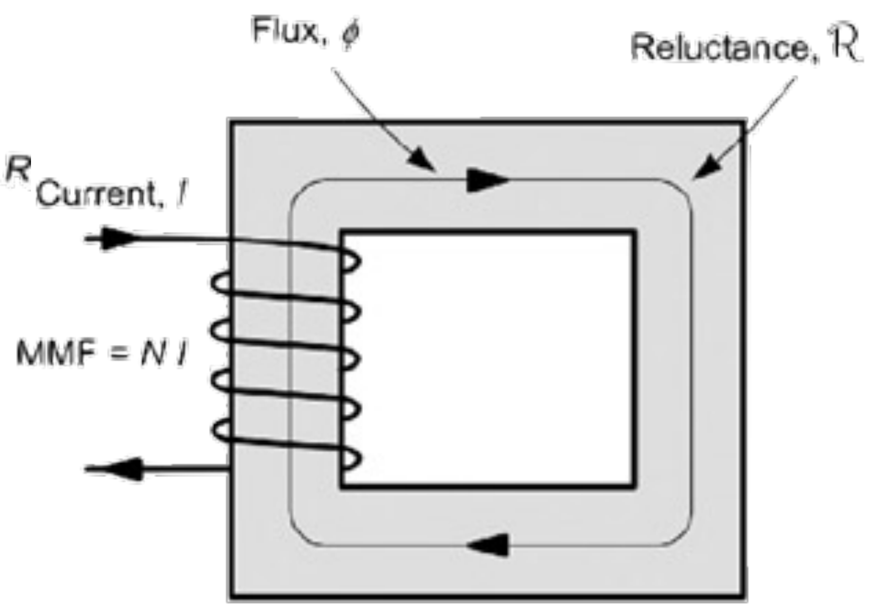
There is a close analogy to electric circuits:



Electric motor



Electric circuit



Magnetic circuit

$$\varepsilon = RI$$

$$R = \frac{l}{\sigma S}$$

$$\mathcal{F} = NI = \mathcal{R}\phi$$

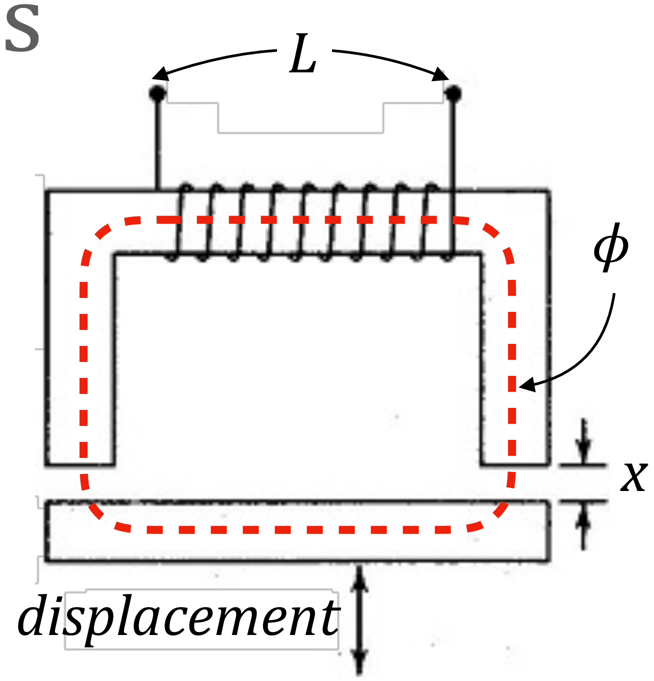
$$\mathcal{R} = \frac{l}{\mu S}$$

Sensing principles — Inductive sensors

Variable reluctance sensors:

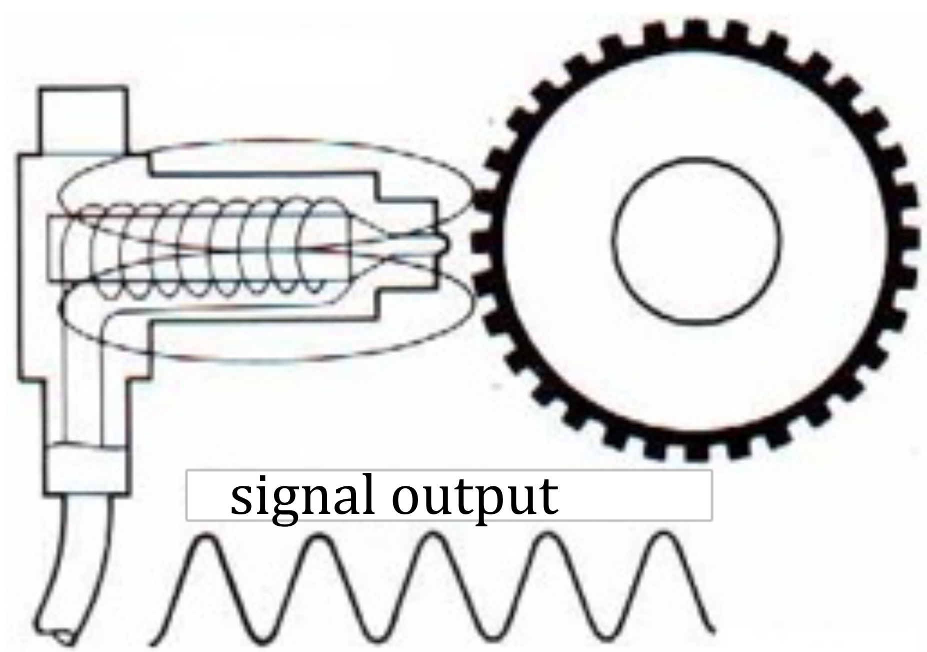
Changes in the reluctance of the magnetic circuit, modifies the magnetic flux.

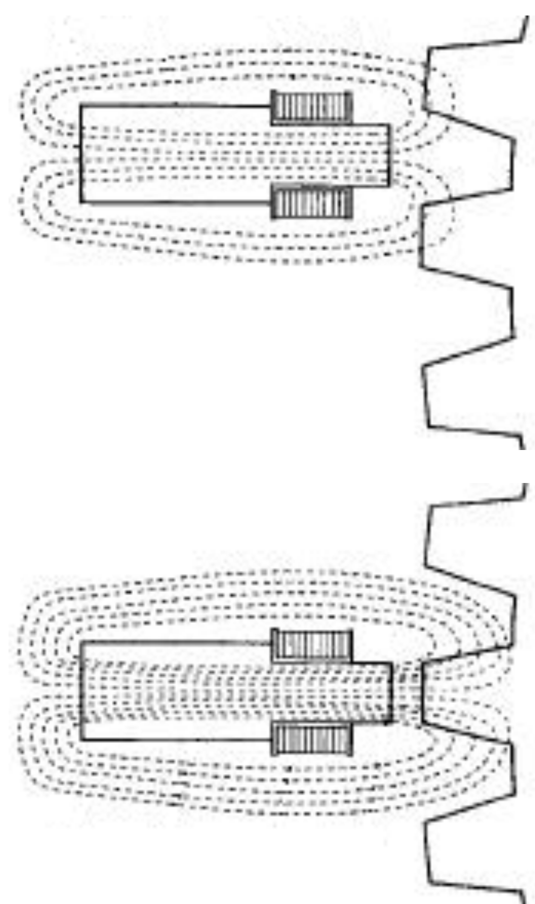
They can detect any ferrous (magnetic) object

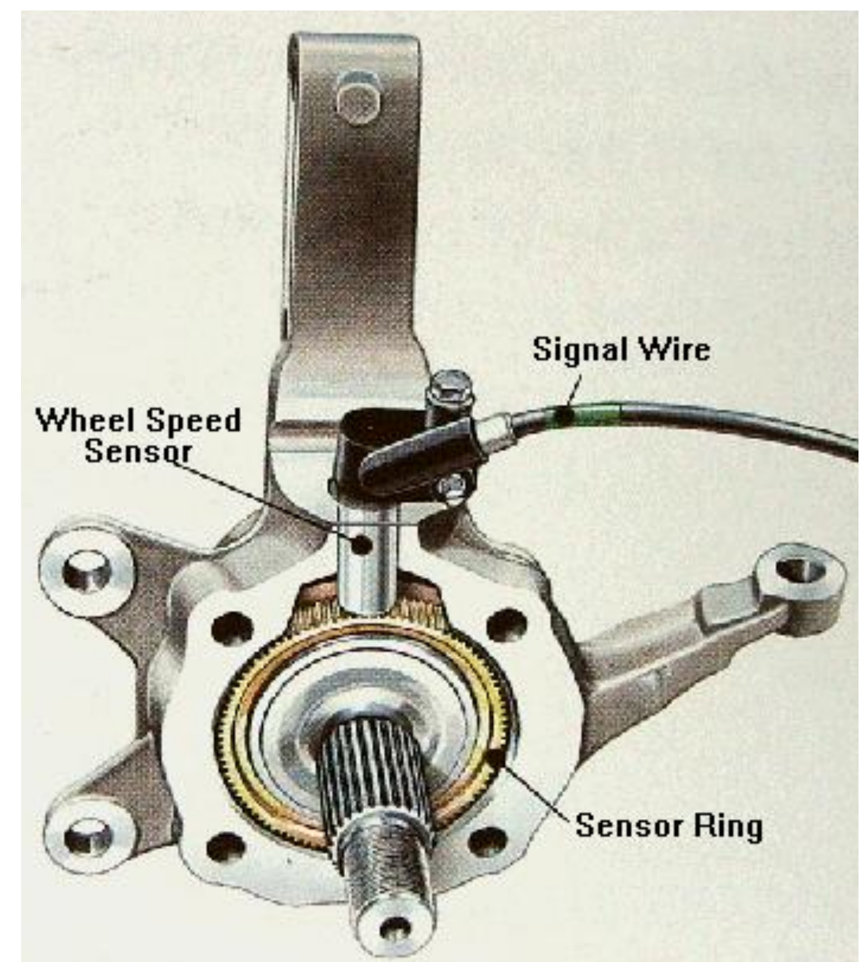


Example:

angular encoder





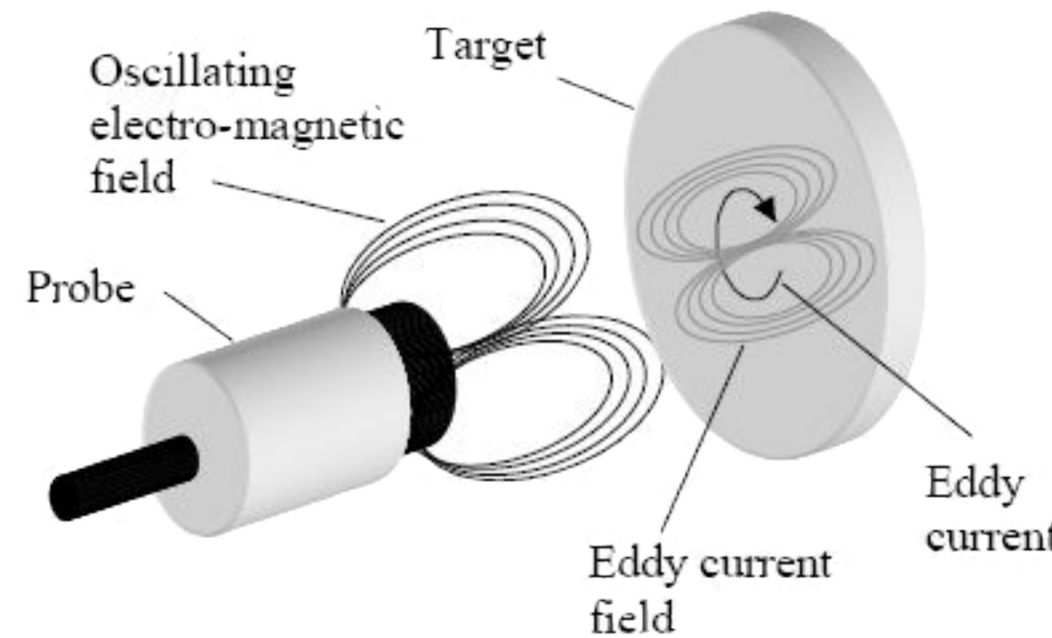


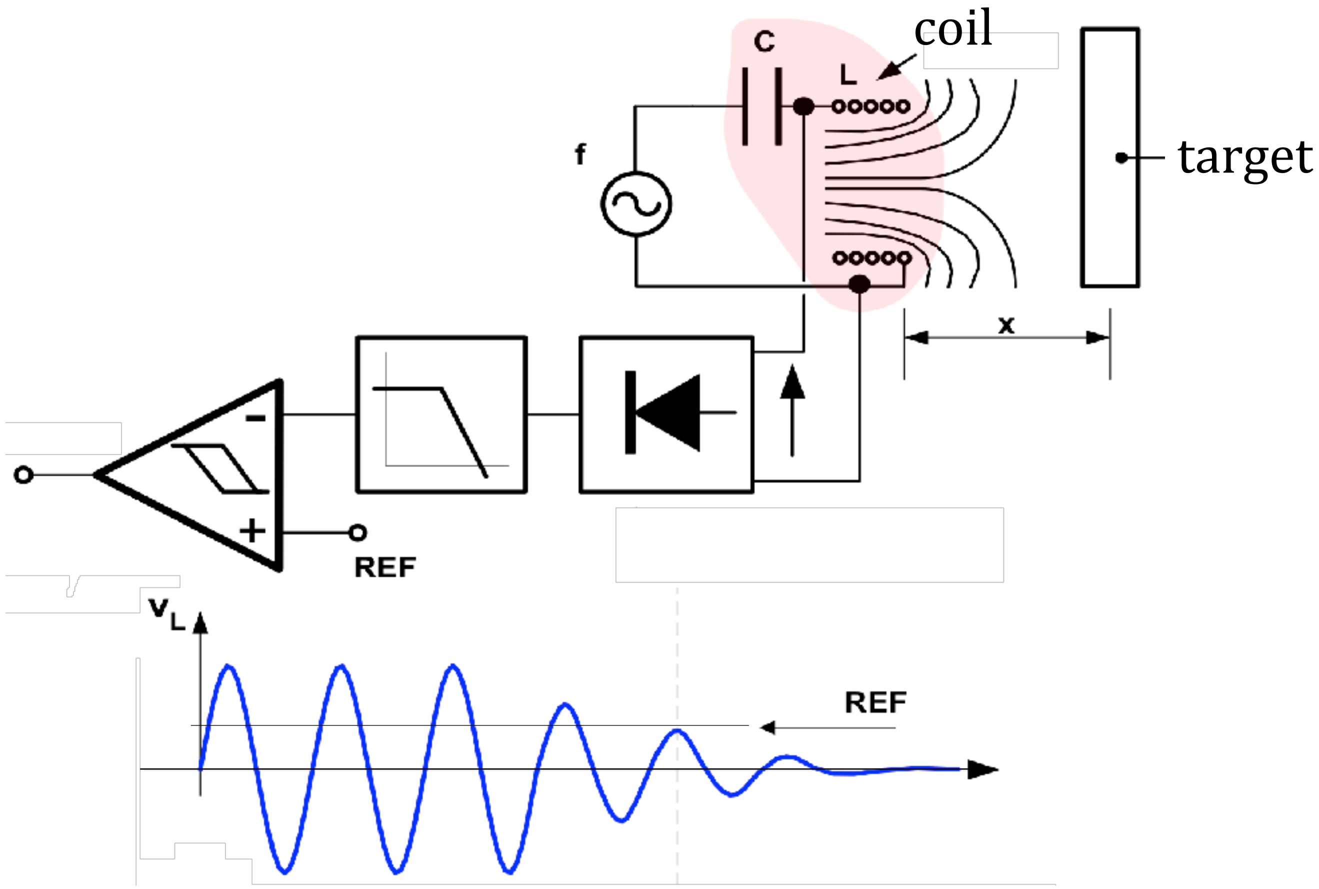
Anti-lock Braking System (ABS)

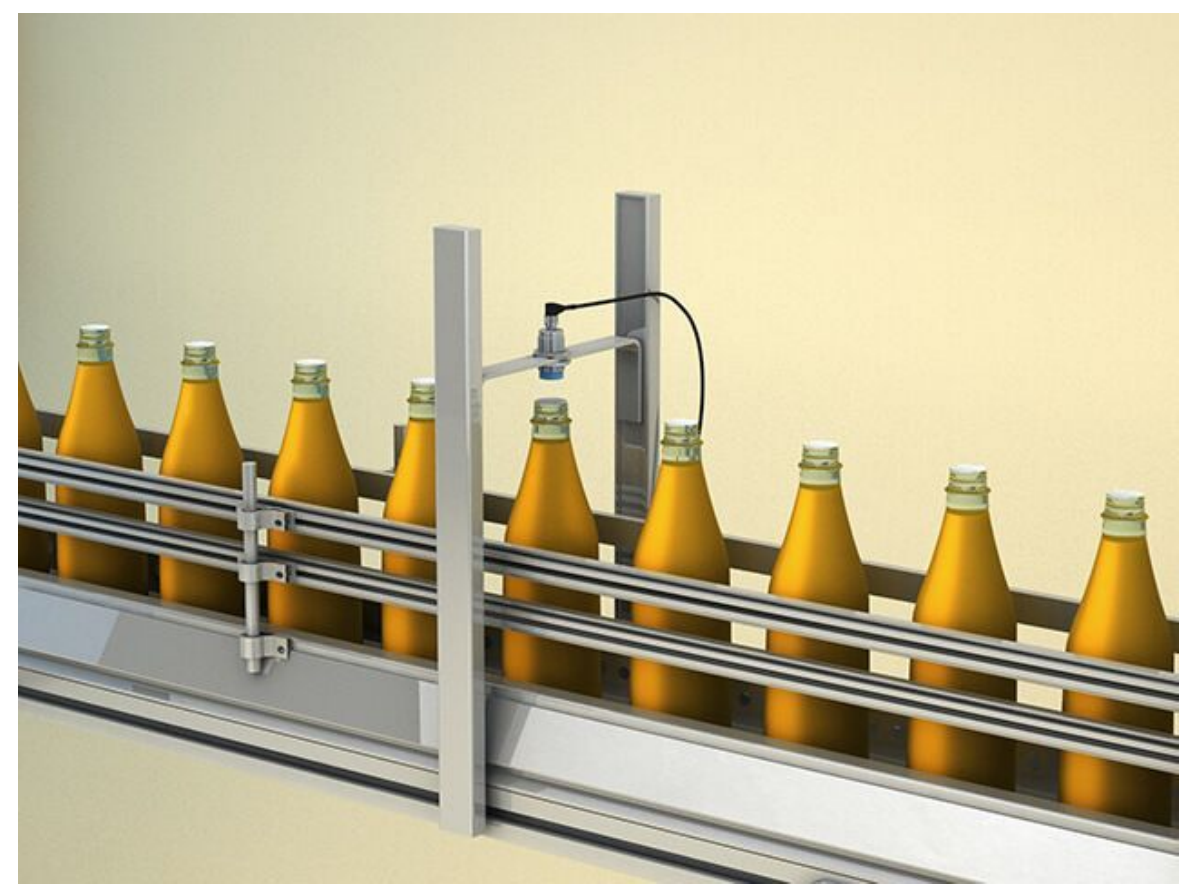
Eddy current sensors:

The alternating magnetic field produces eddy-currents in the target, which not need to be magnetic, only a good conductor.

Used as presence detectors.



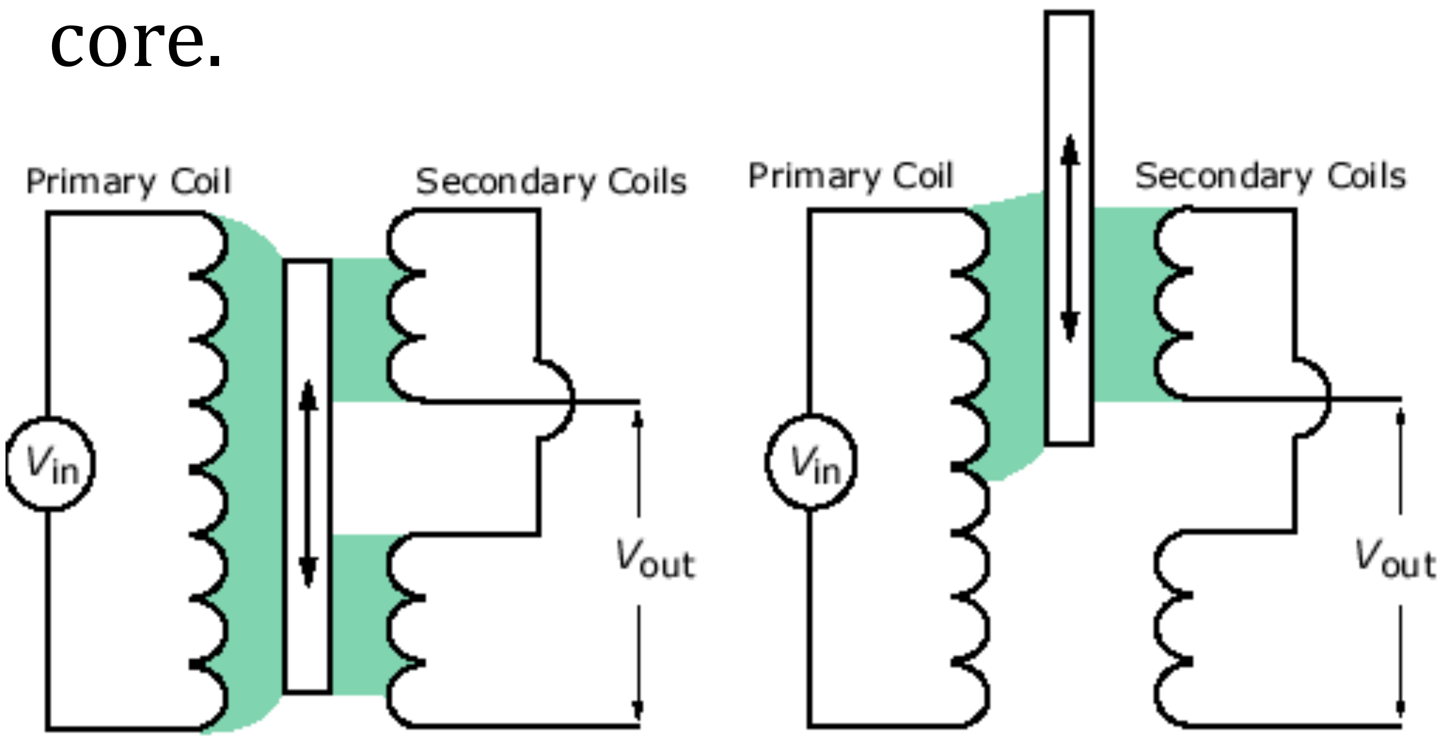


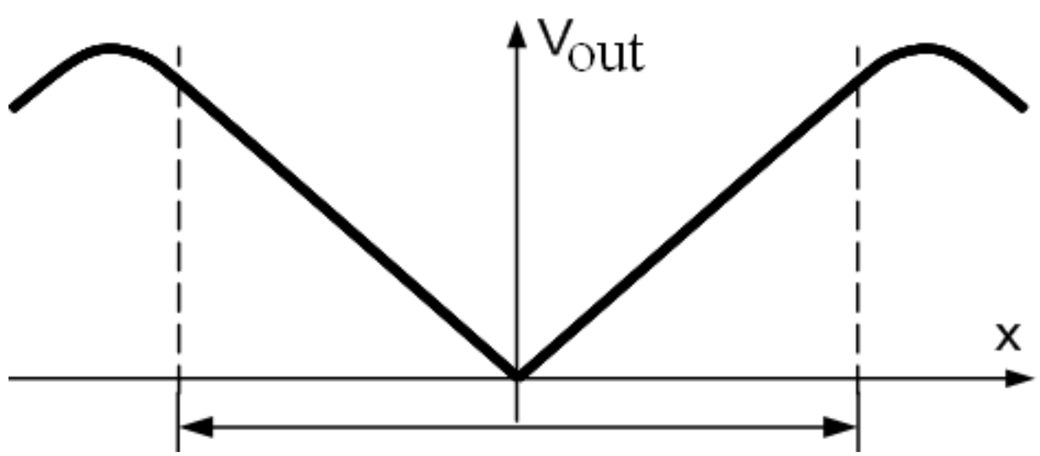


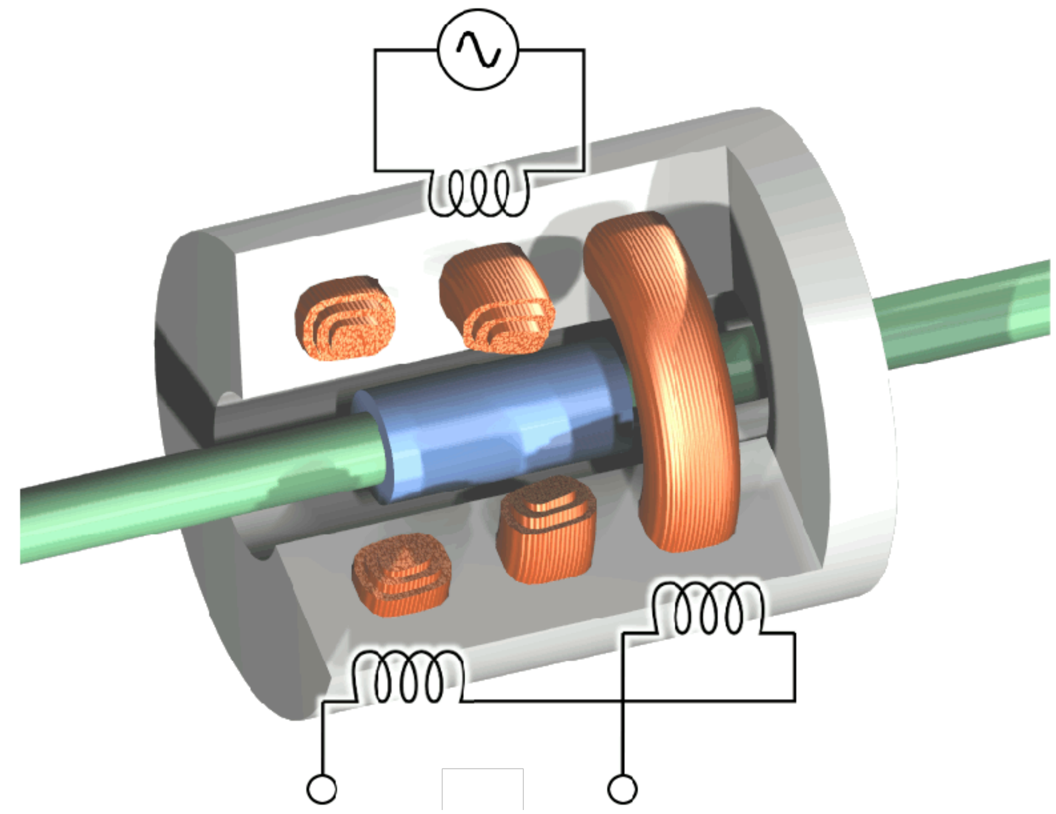
source: contrinex.com

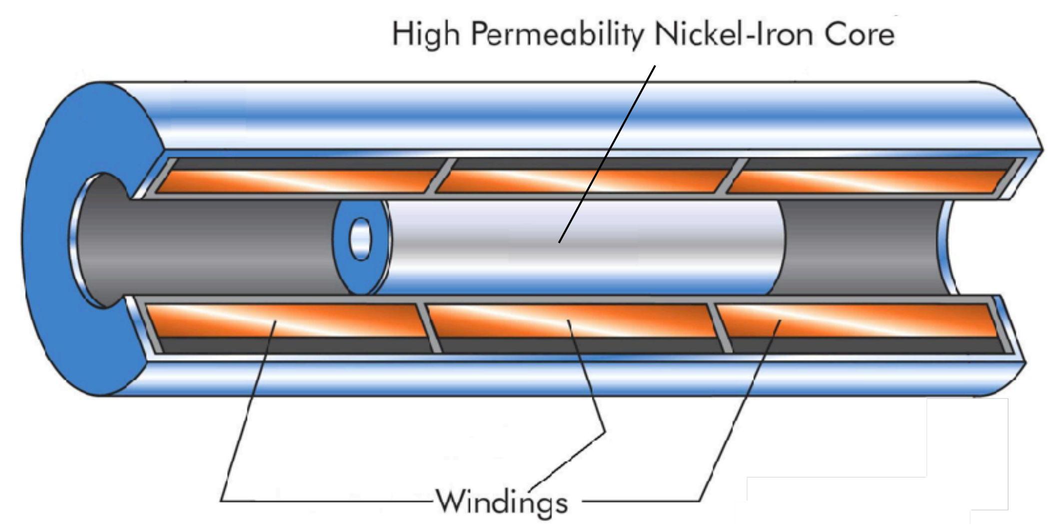
Linear variable differential transformers (LVDT):

The mutual inductance between the excitation coil and the sensing coils is modified by the position of a magnetic core.





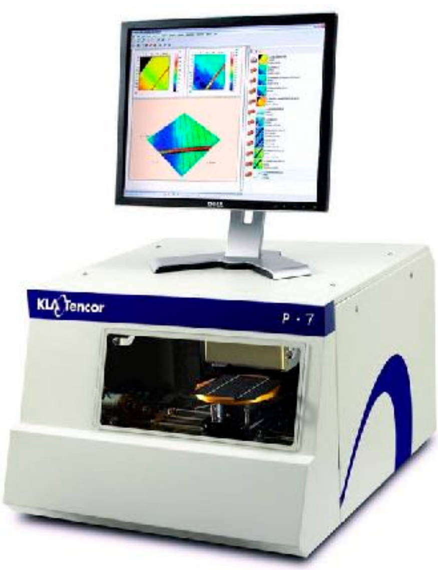


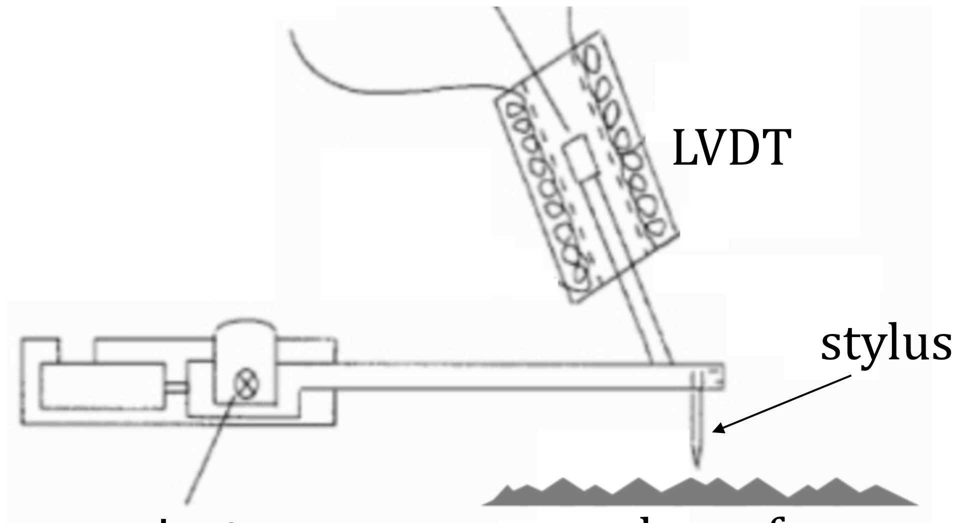


Sensing principles Inductive sensors

LVDTs present excellent performance for position sensing.

- *surface profilometry*

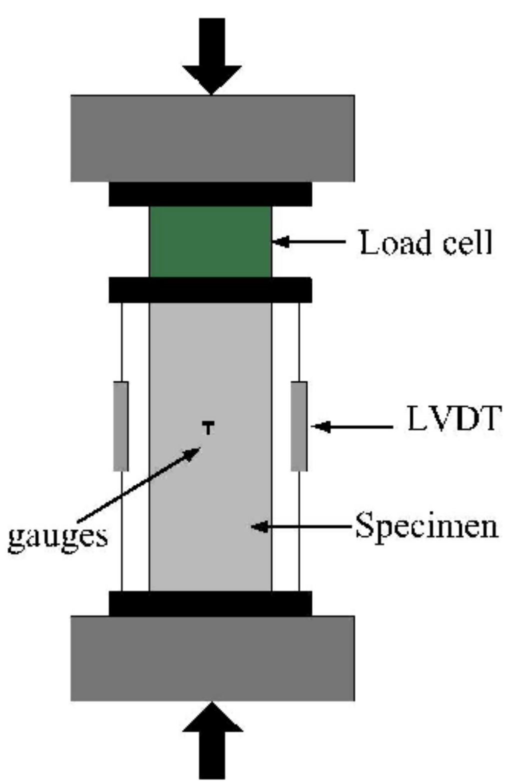




source: kla-tencor.com

- *civil engineering*

- *materials testing*

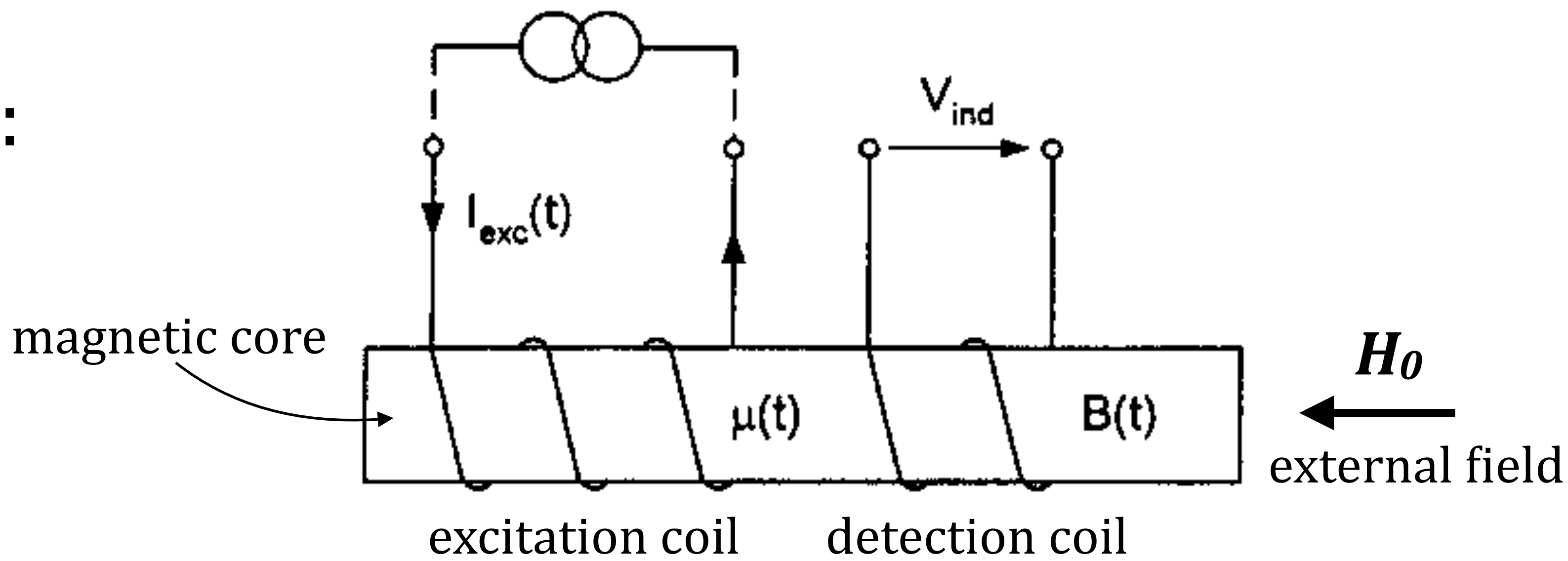


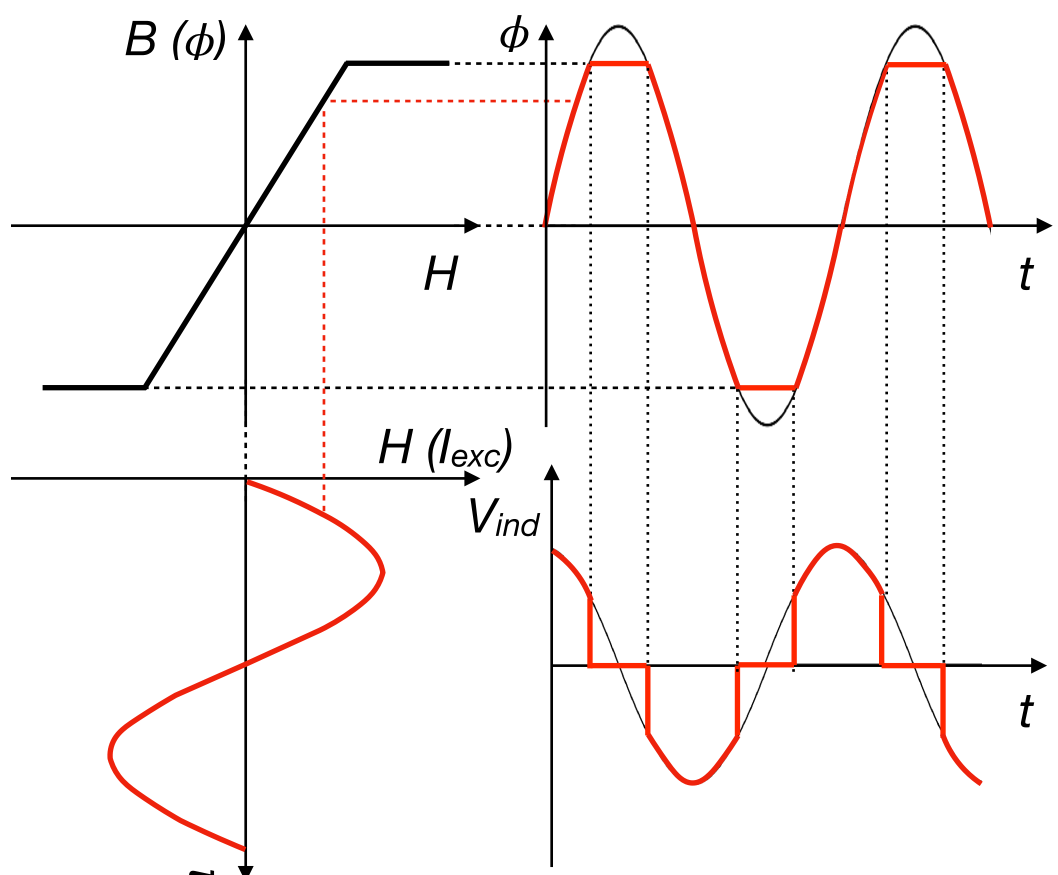
- *metrology*
- *CNC machining tools*
- *...*

Fluxgate sensors

Exemplify the use of non-linearities in magnetic sensors.

Basic set-up:

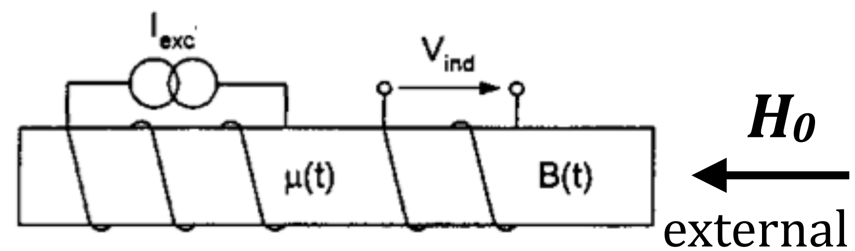




The excitation drives the core to saturation.

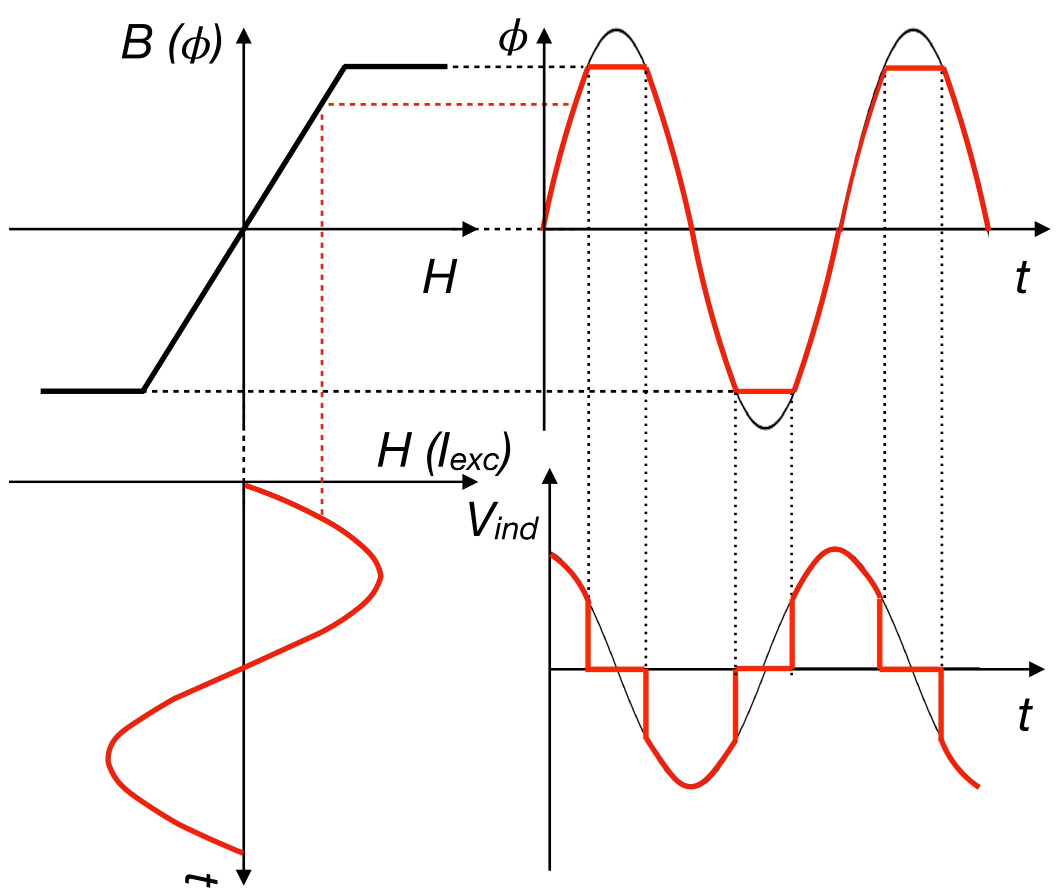
The flux in the detection coil becomes "gated"

Fluxgate signals:



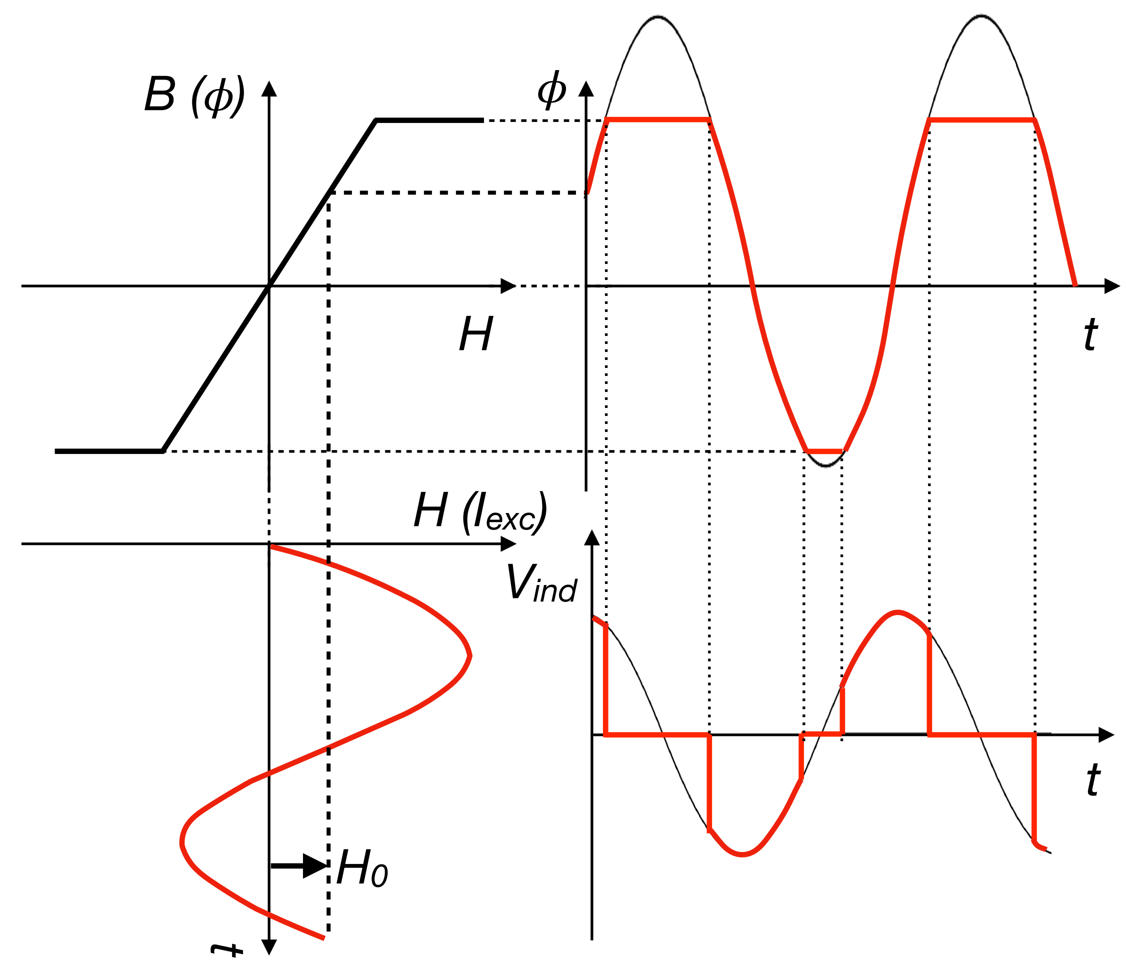
external field

$H_0 = 0$ (no external field)



Only odd harmonics

$H_0 > 0$ (small external field)



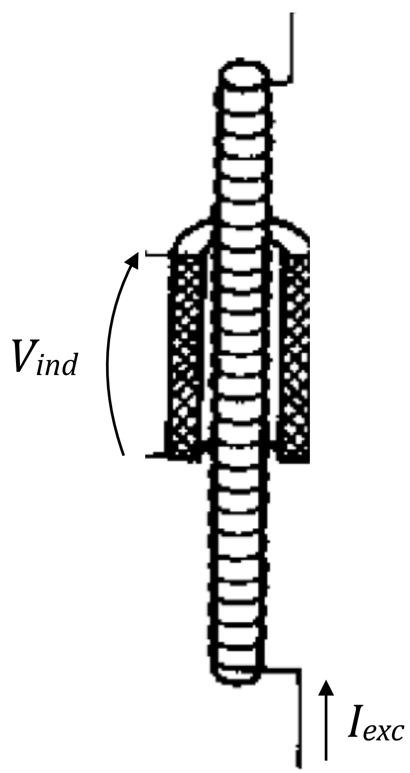
even harmonics

The amplitude of the second harmonic is proportional to the external field.

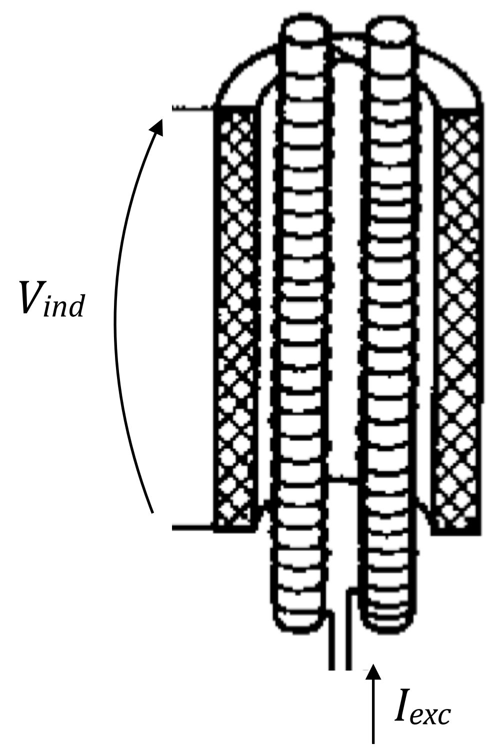
Sensing principles — Inductive sensors

The direct flux in the sensing coil complicates the measurement. A differential approach is better:

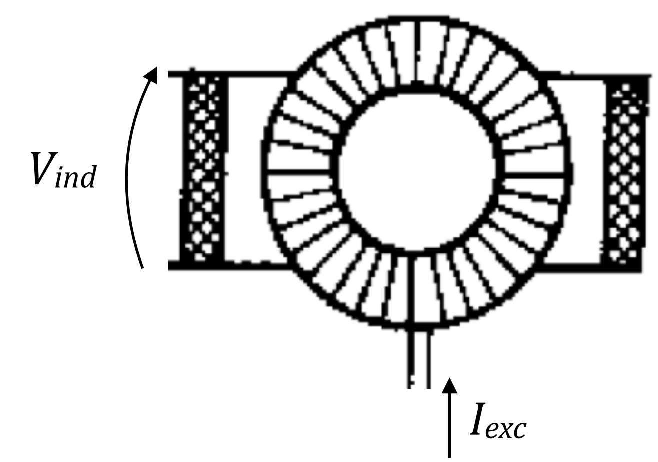
single core fluxgate
(original configuration)

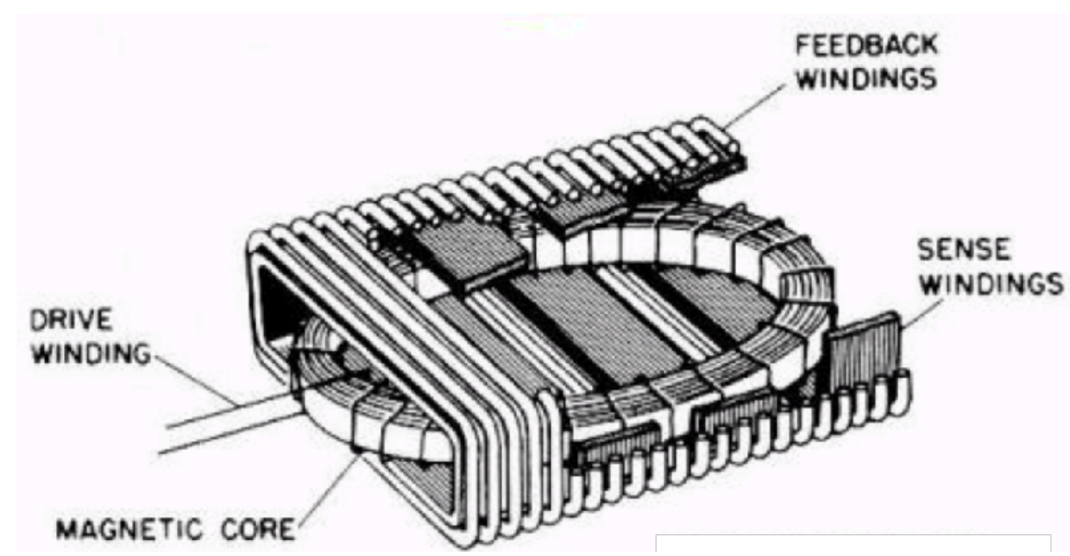


double core fluxgate
(differential configuration)



ring type fluxgate
(simplified evolution
of double core)

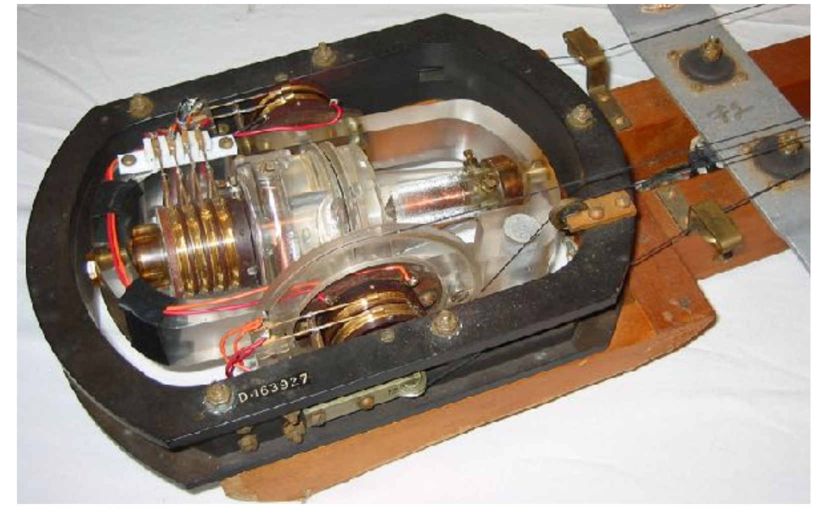




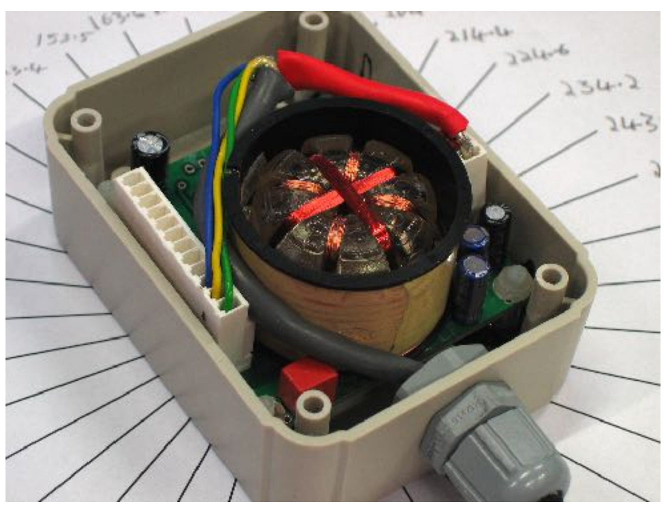
Fluxgate are very sensitive vectorial sensors (magnitude and direction)

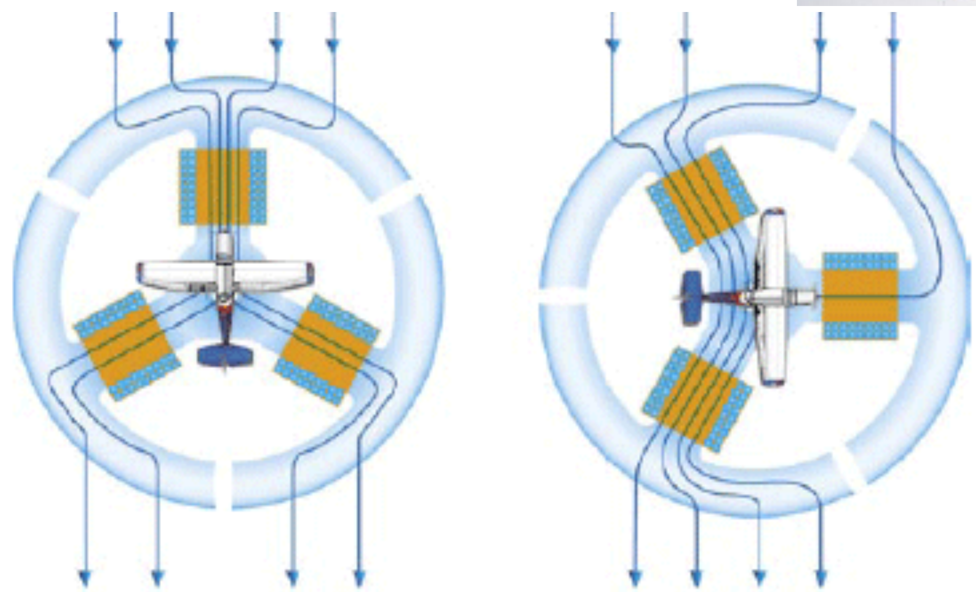
Resolution 10 pT and 1 nT precision.

- submarine detection
  (airborne magnetometer used in WWII)



source: geomag.nrcan.gc.ca





source: flight-mechanic.com

- aircraft and land vehicles navigation

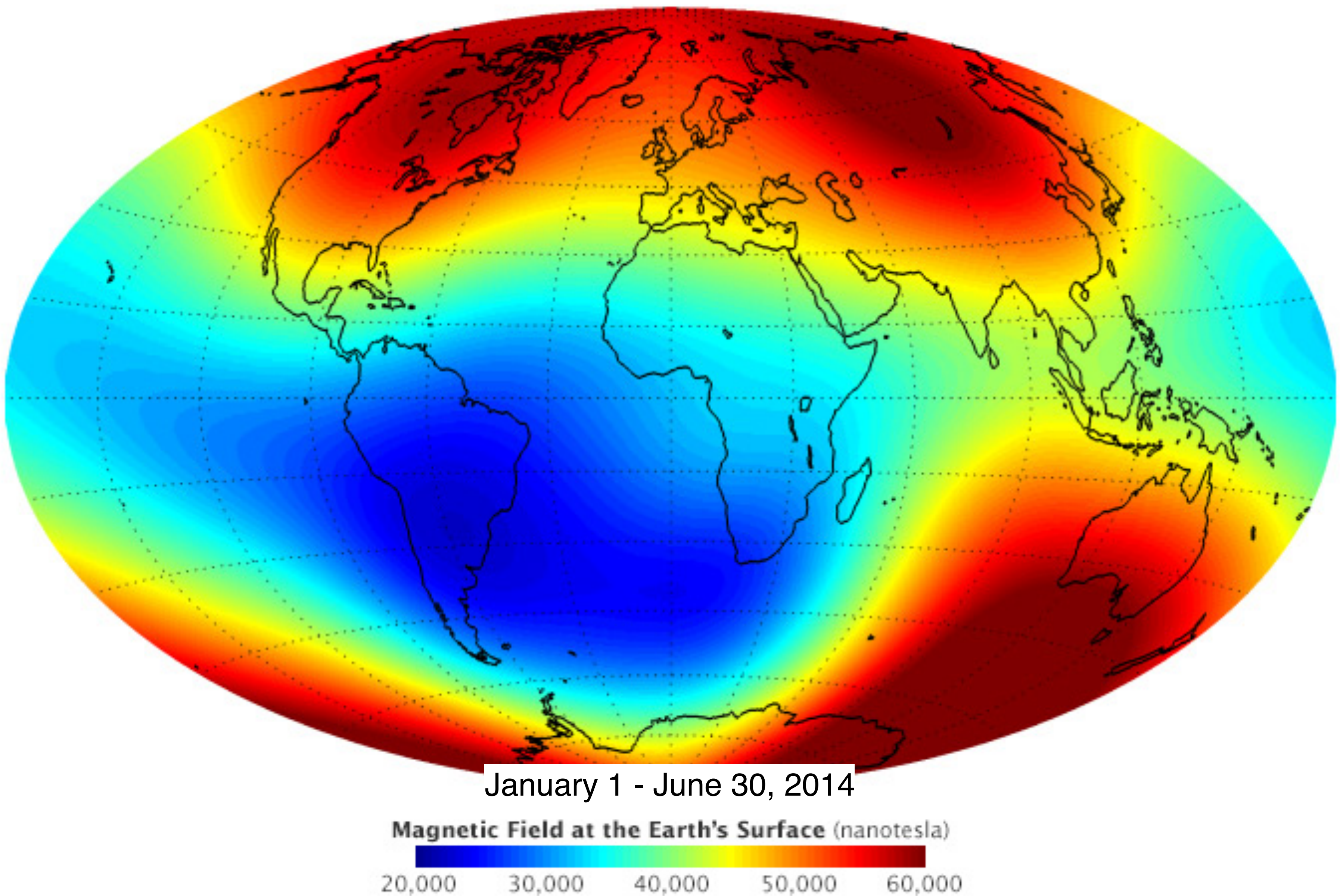
- space applications

- laboratory and geophysical measurements

source: space.dtu.dk

Earth surface magnetic field

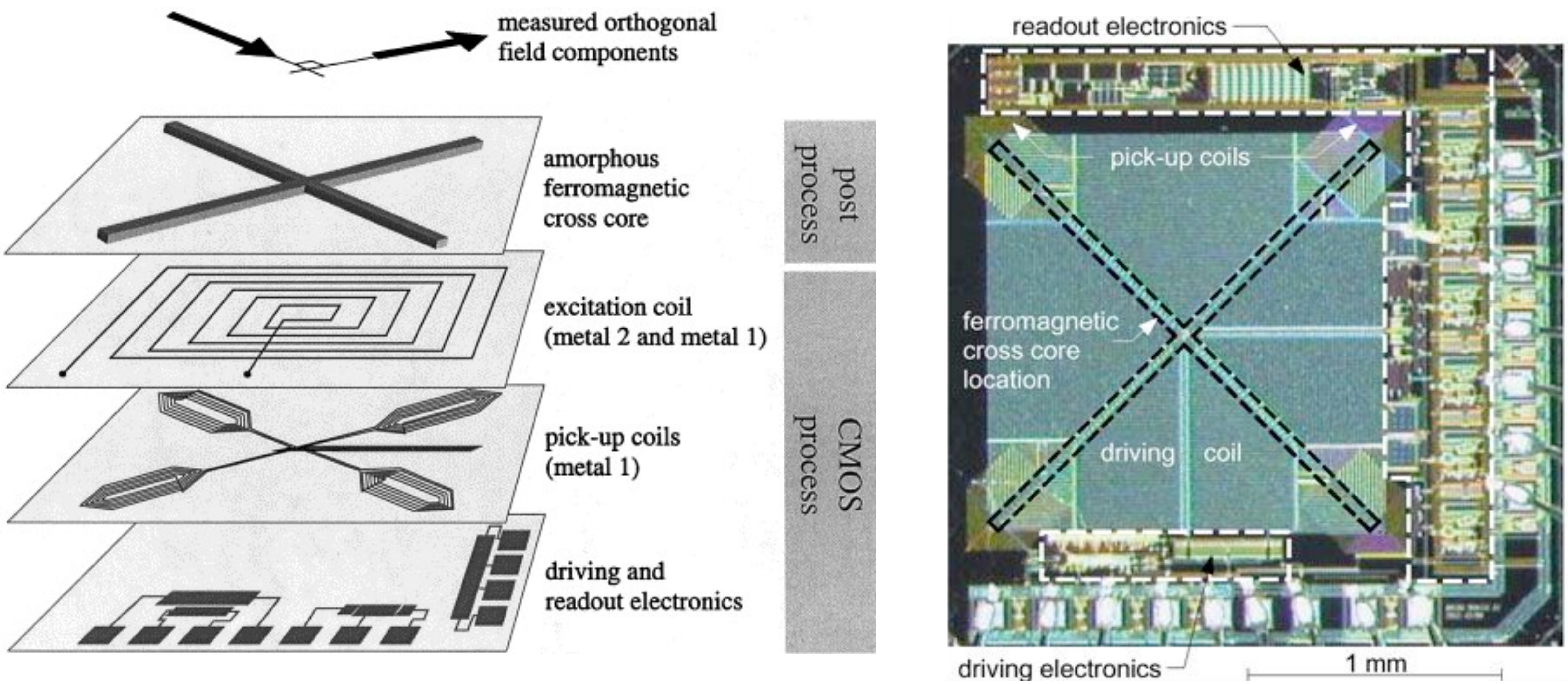
Measured by Swarm constellation of three satellites (European Space Agency).
Sensors form Technical University of Denmark (DTU).



http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm/Swarm_reveals_Earth_s_changing_magnetism

Fluxgates tend to be bulky.
Micromachined devices are possible, but with decreased performance.

Micro fluxgate fabricated with CMOS technology, incorporating excitation and signal conditioning.



L. Chiesi et al., Sens. Actuators A **82** (2000) 174-180

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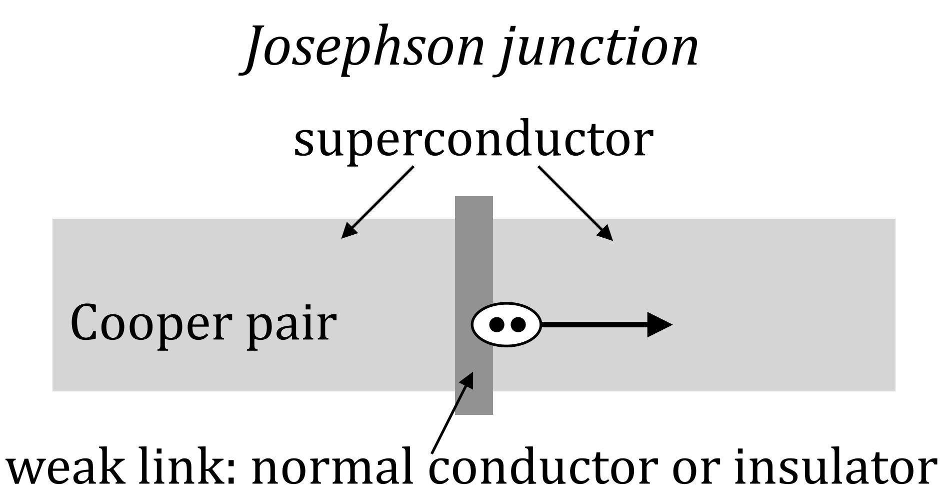
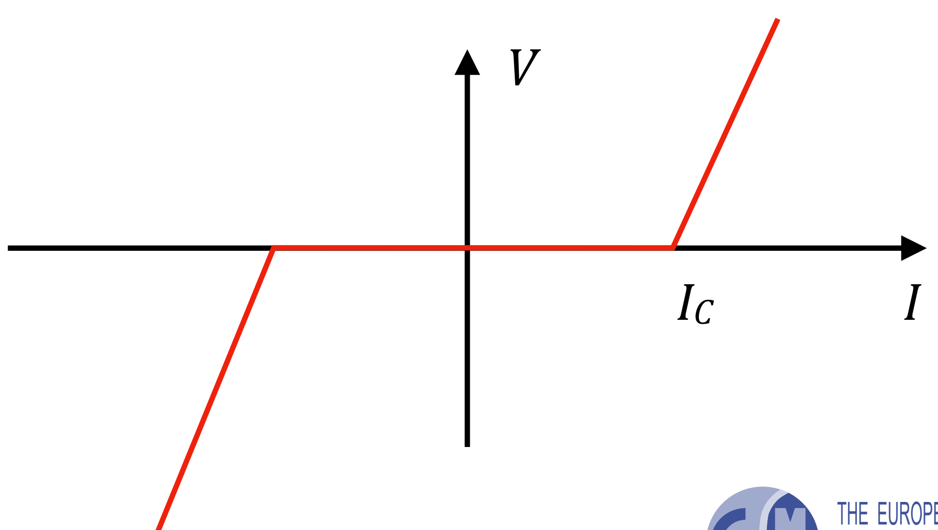
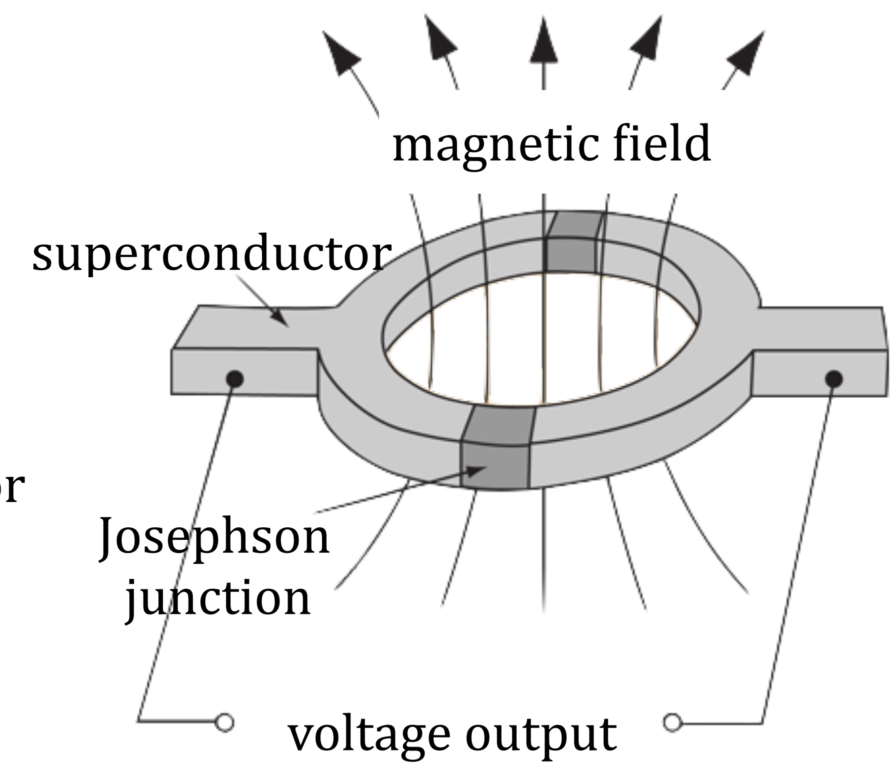
2. Sensing principles and examples
SQUID sensors

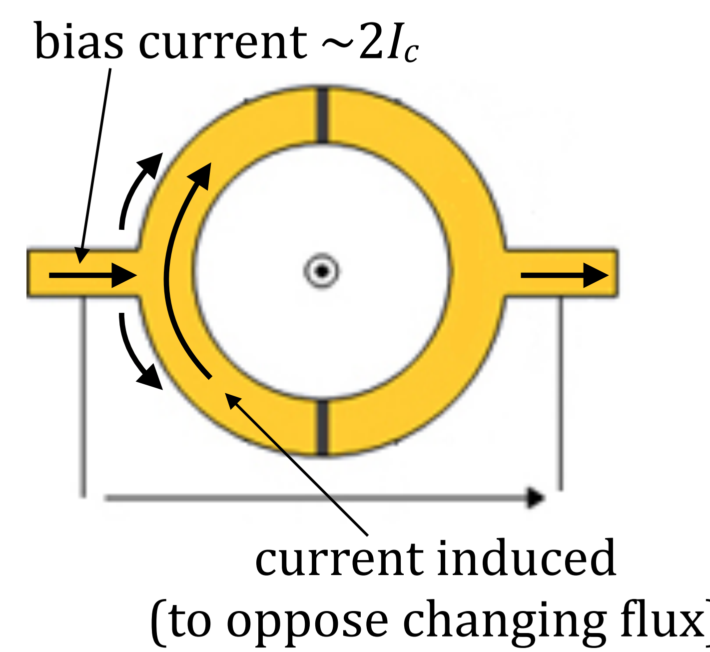
Superconducting QUantum Interference Devices are based on

- superconductivity (current flow without resistance)
- Josephson effect (tunnelling of supercurrents)



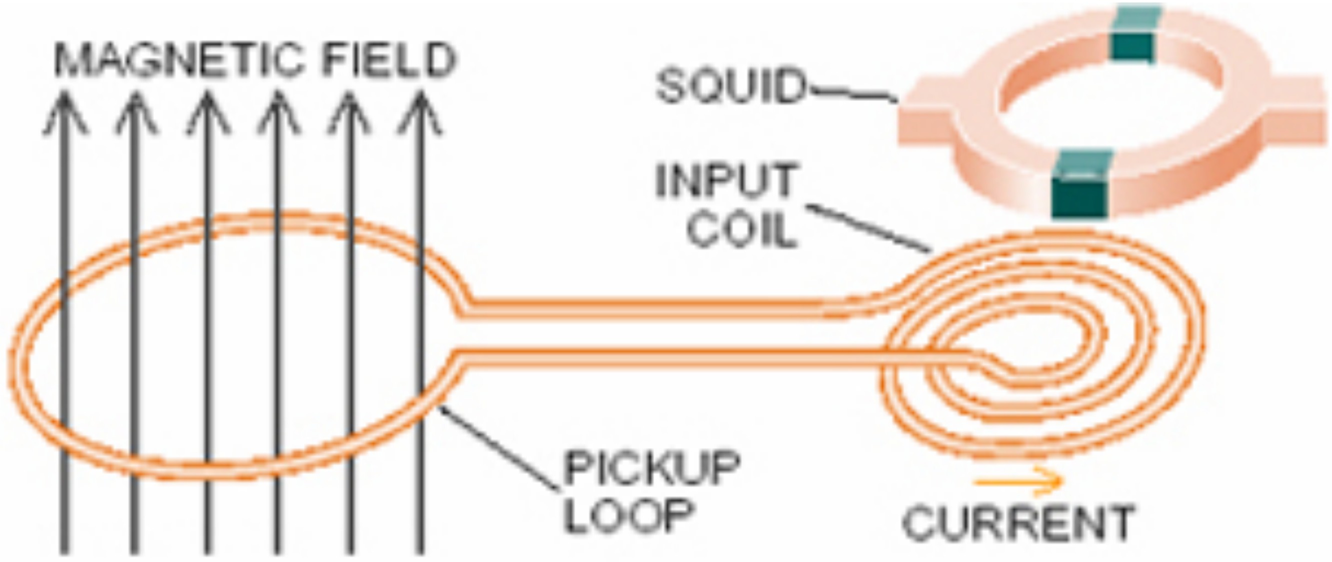






In applications, the flux is translated to the SQUID sensor using a transformer made of superconducting wire to:

- protect the SQUID from external interferences.
- increase the resolution (above the limit of the quantum flux: $\phi_0 = 2.07 \times 10^{-15}$ Wb).



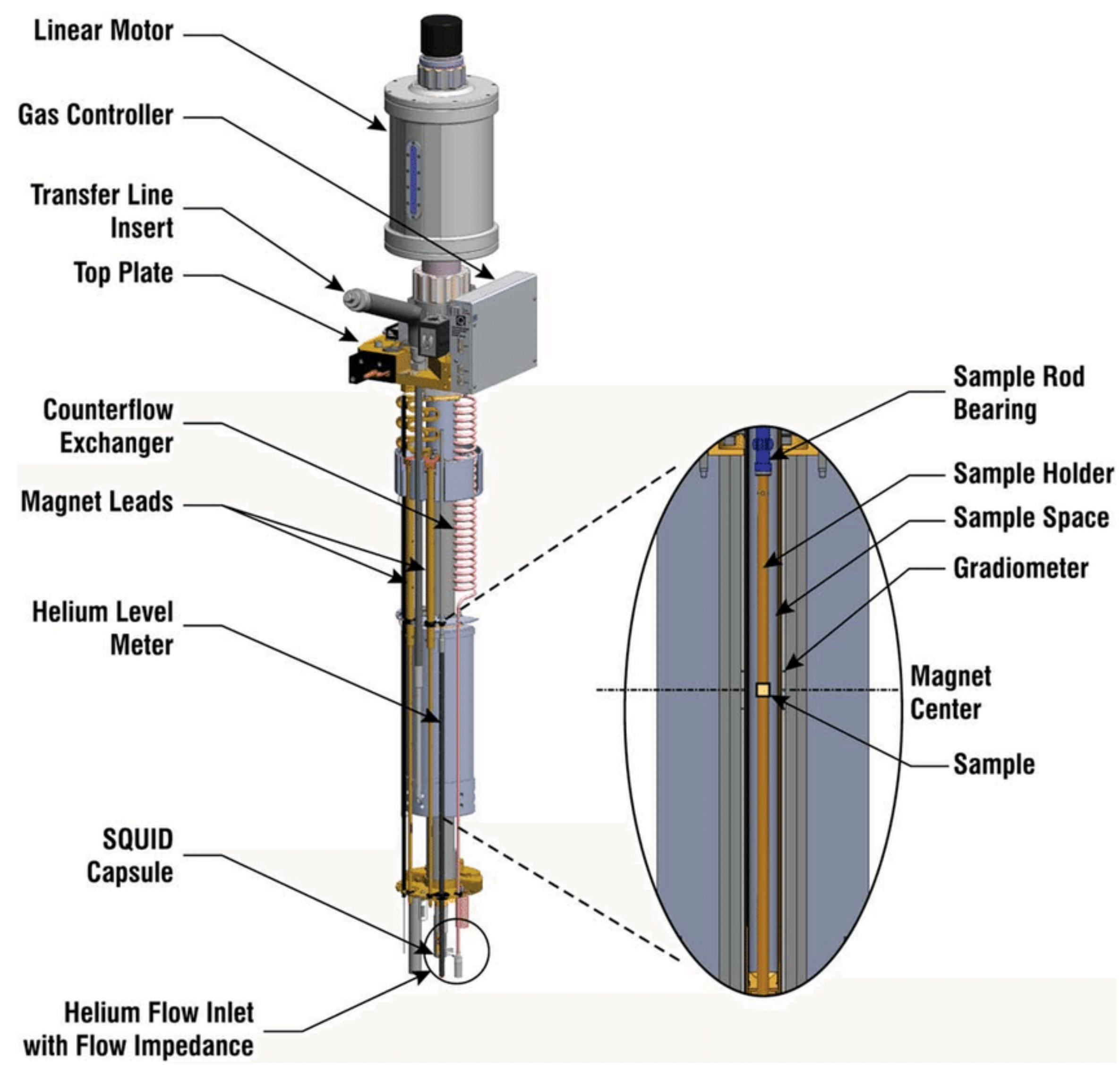
There are both ac and dc SQUIDS. Today they can also be made with high temperature superconductors.

Best dc SQUIDS reach resolutions of the order of 1 fT (10^{-15} T).

The main drawback: complex equipment due to low temperatures.

SQUIDs are used to measure very small magnetic fields.

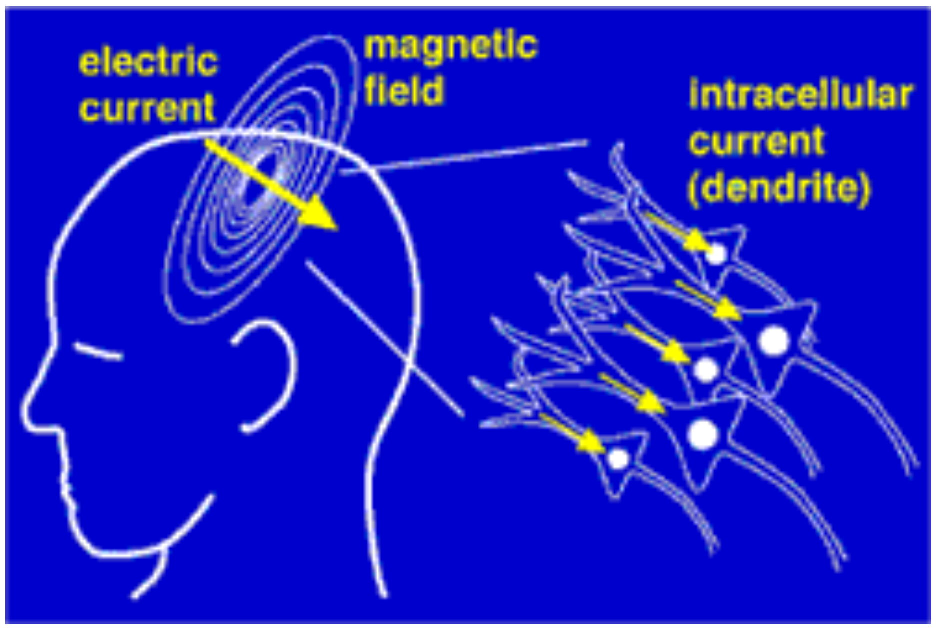
Magnetometers

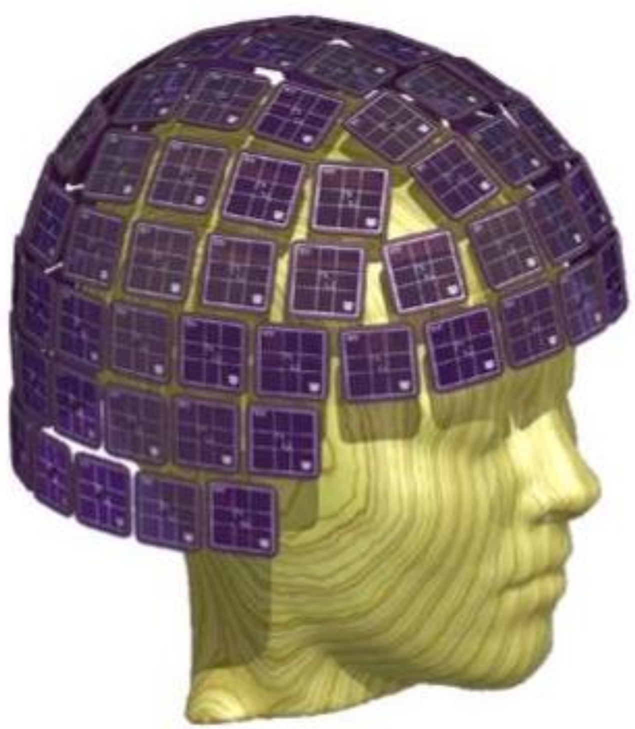


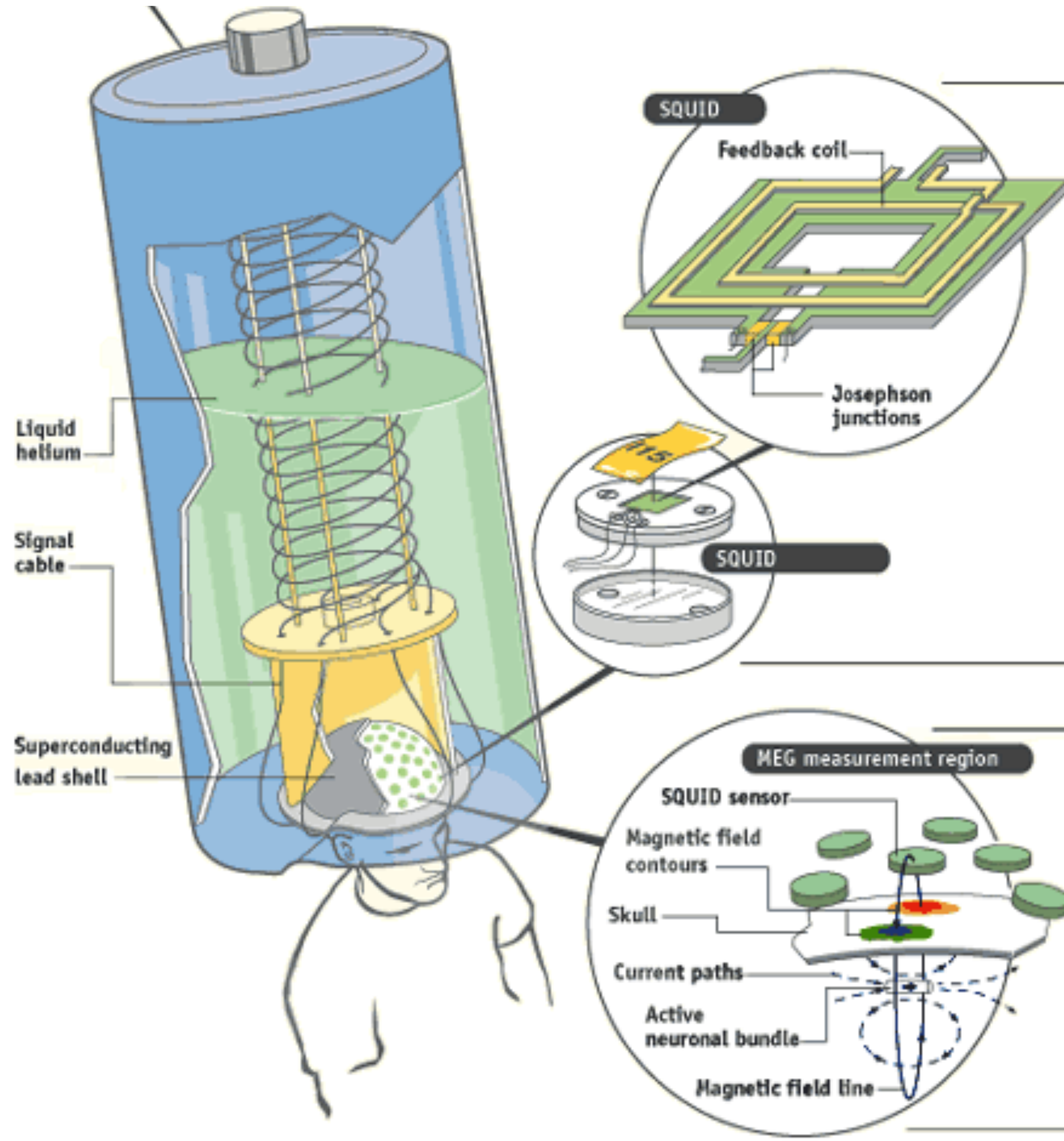
source: lot-qd.de LOT-QuantumDesign

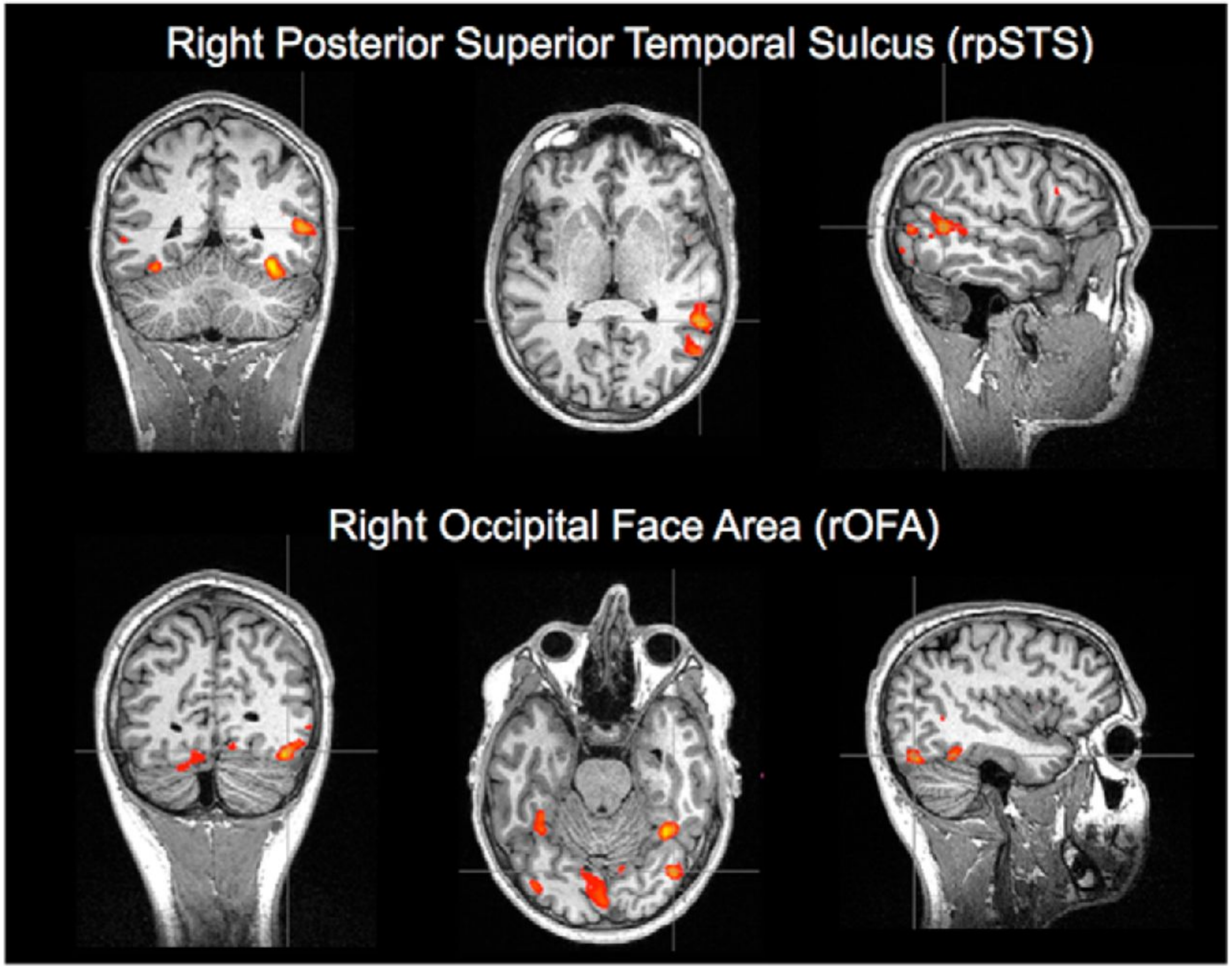
Sensing principles SQUID sensors

Magneto-encephalography



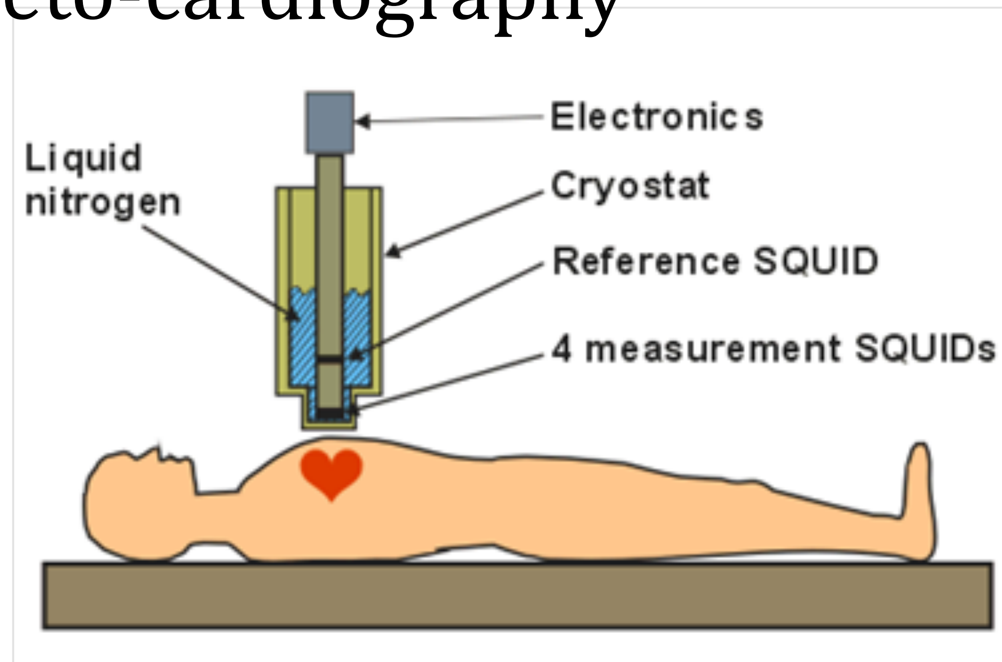


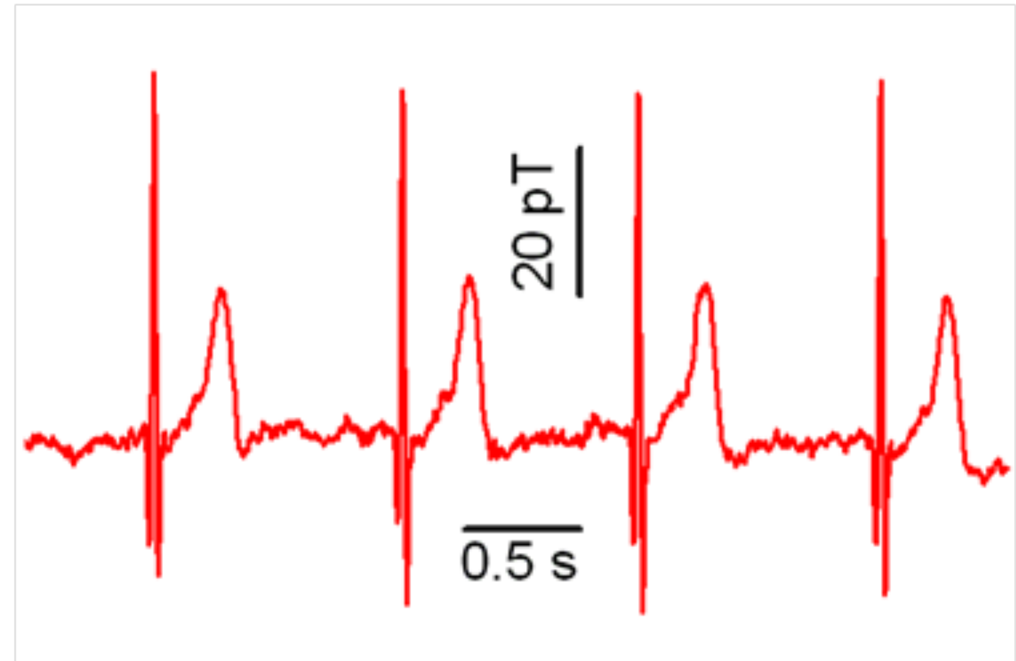




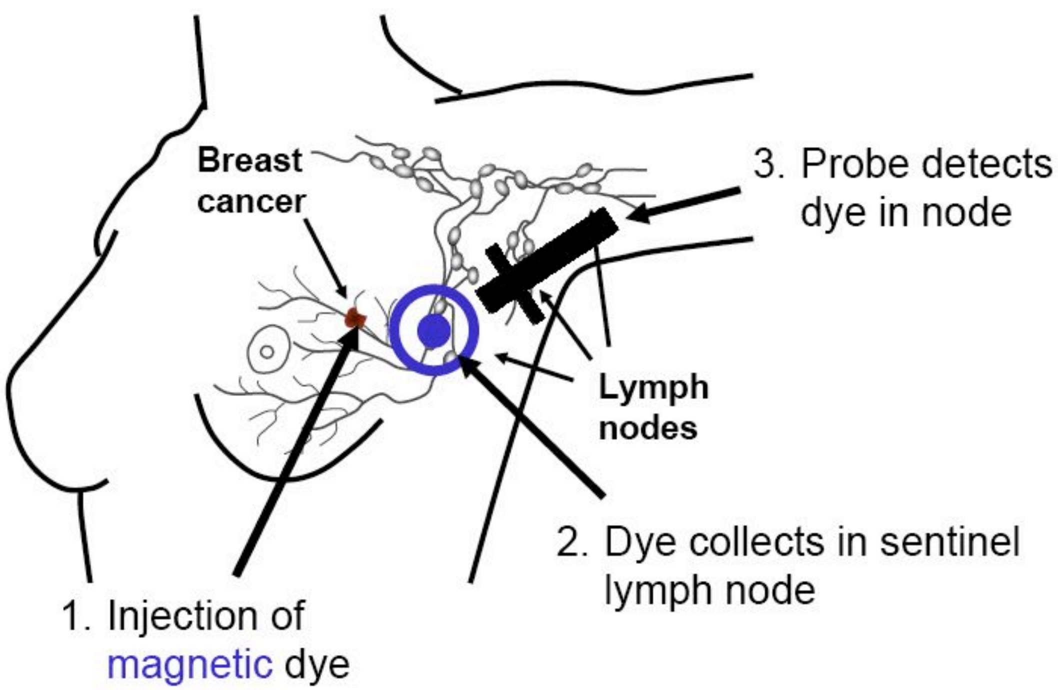
*D. Pitcher, J. Neuroscience, **34** (2014) 9173-9177*

Magneto-cardiography

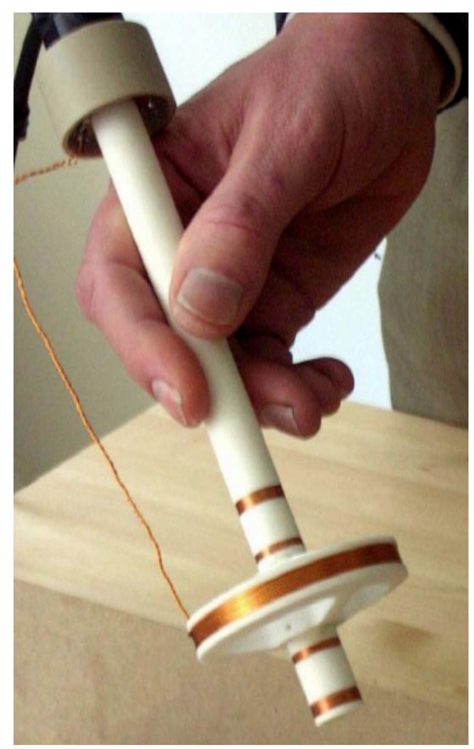




Diagnostic tools



source: Prof. Q. Pankhurst



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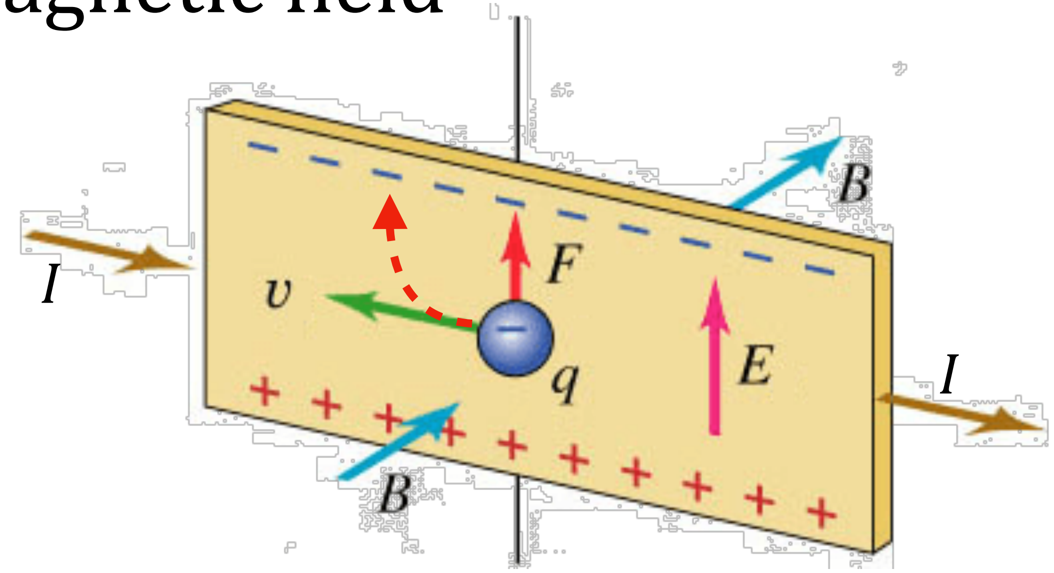
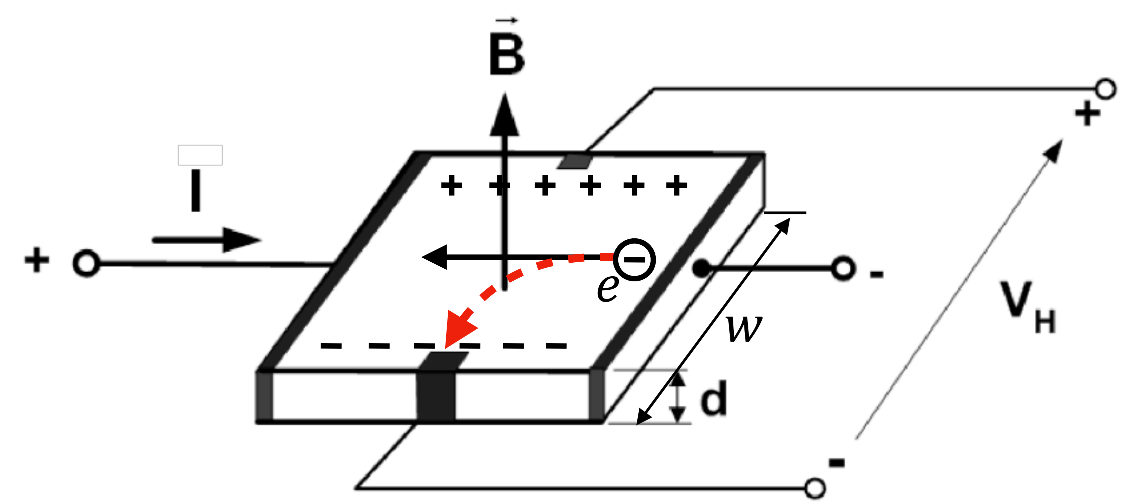
   ***c.* Hall effect sensors** *(magnetic compass, encoders).*
   d. Magnetoresistance sensors: AMR, GMR, TMR.
   e. Magnetoelastic sensors *(torque sensors, anti-shoplifting labels).*

2. Sensing principles and examples
Hall sensors

Hall effect

Caused by the interaction of electric current carriers with the magnetic field





Lorentz force on carrier: $\vec{F} = q\vec{v} \times \vec{B}$

Electric field by charge buildup: $E = V_H / w$

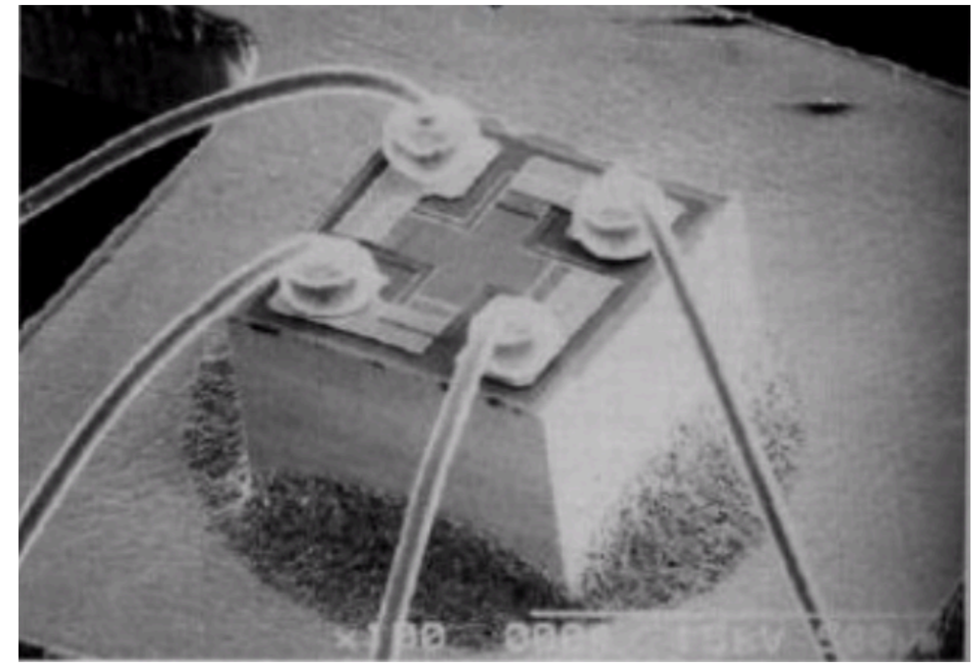
Carrier velocity: $v = \dfrac{I}{newd}$

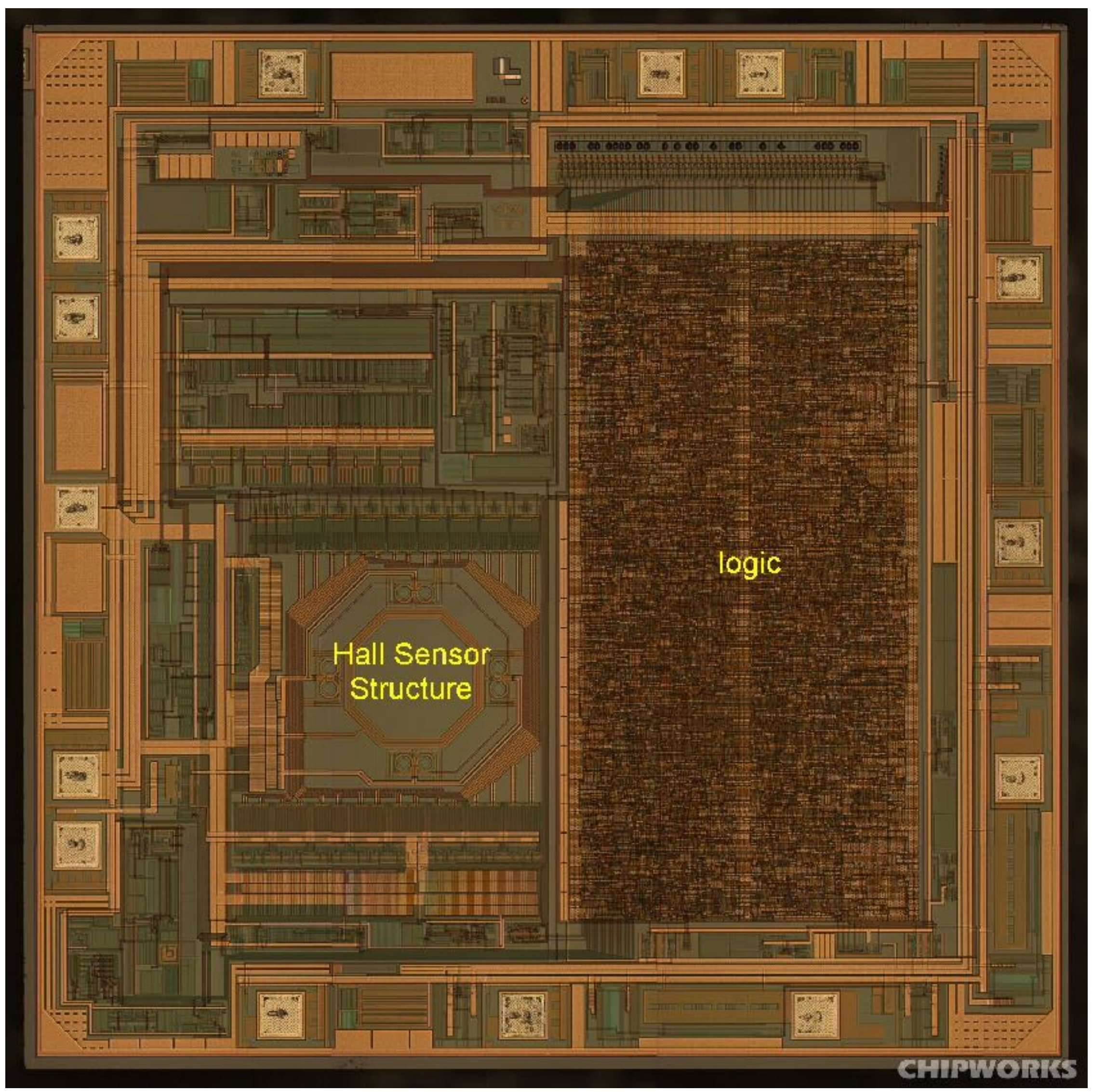
$$V_H = \frac{IB}{nde}$$

I = 100 mA
B = 50 mT
d = 120 µm
$n = 10^{22}$ m^{-3}

V_H = 25 mV

Made of semiconductor materials:
Si, InSb, GaAs, etc.

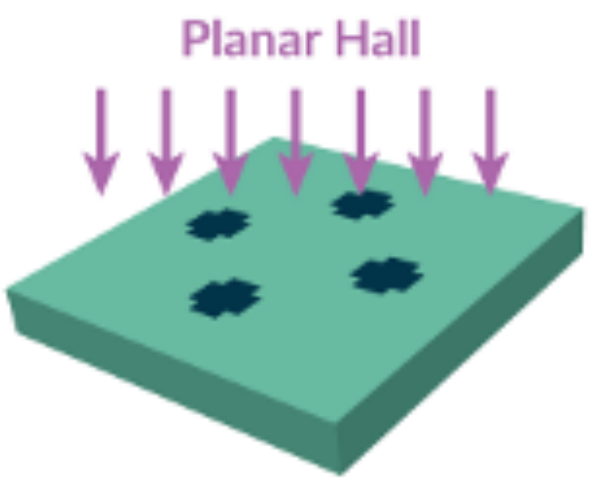




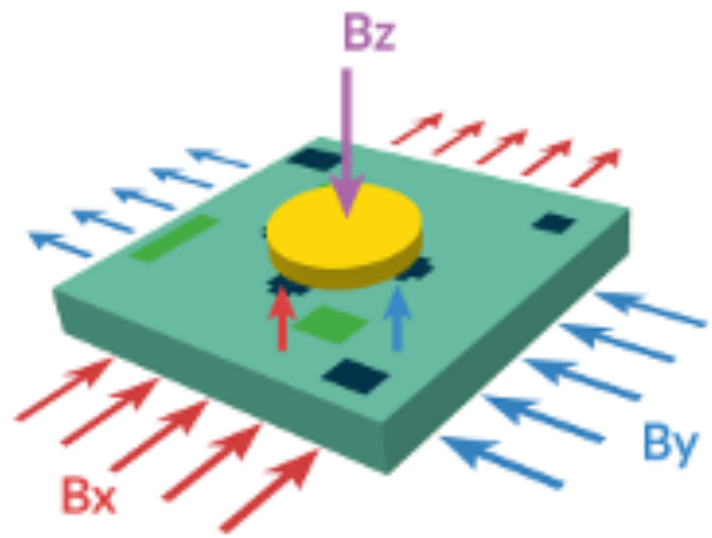
Hall IC: Asahi Kasei Microdevices akm.com

Hall ICs:
fully integrated in a IC chip with electronics to provide signal conditioning (amplification, offset correction, signal processing, …)

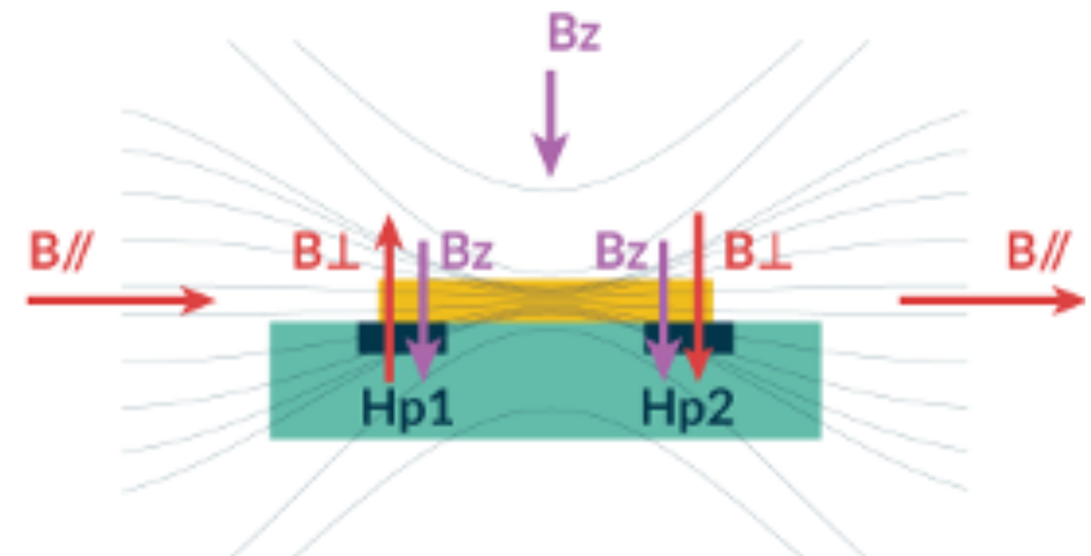
Sensitivity enhancement and three axis measurement are possible with a magnetic field concentrator:



Hall sensors are sensible to perpendicular fields

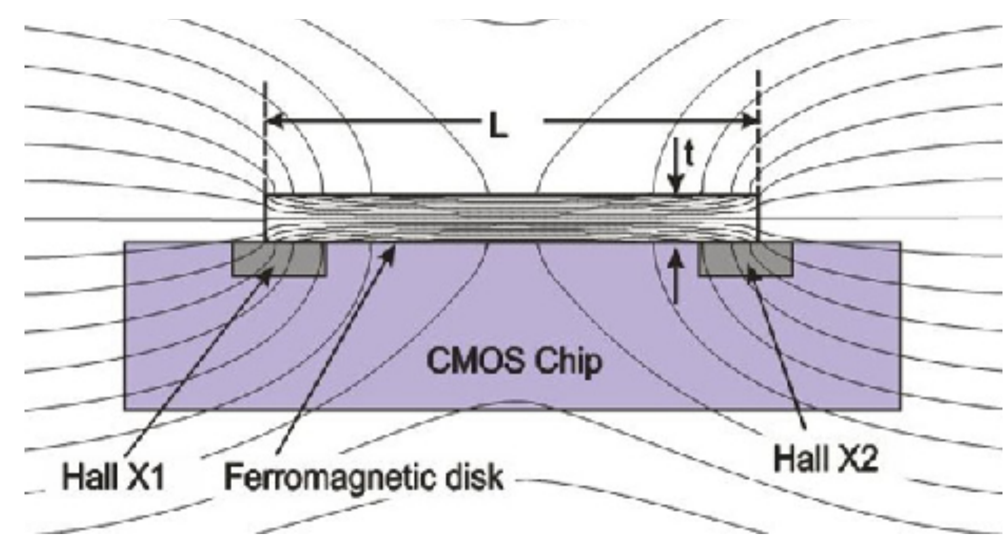


A magnetic concentrator (permalloy film) is deposited on top



The in-plane fields develop perpendicular components

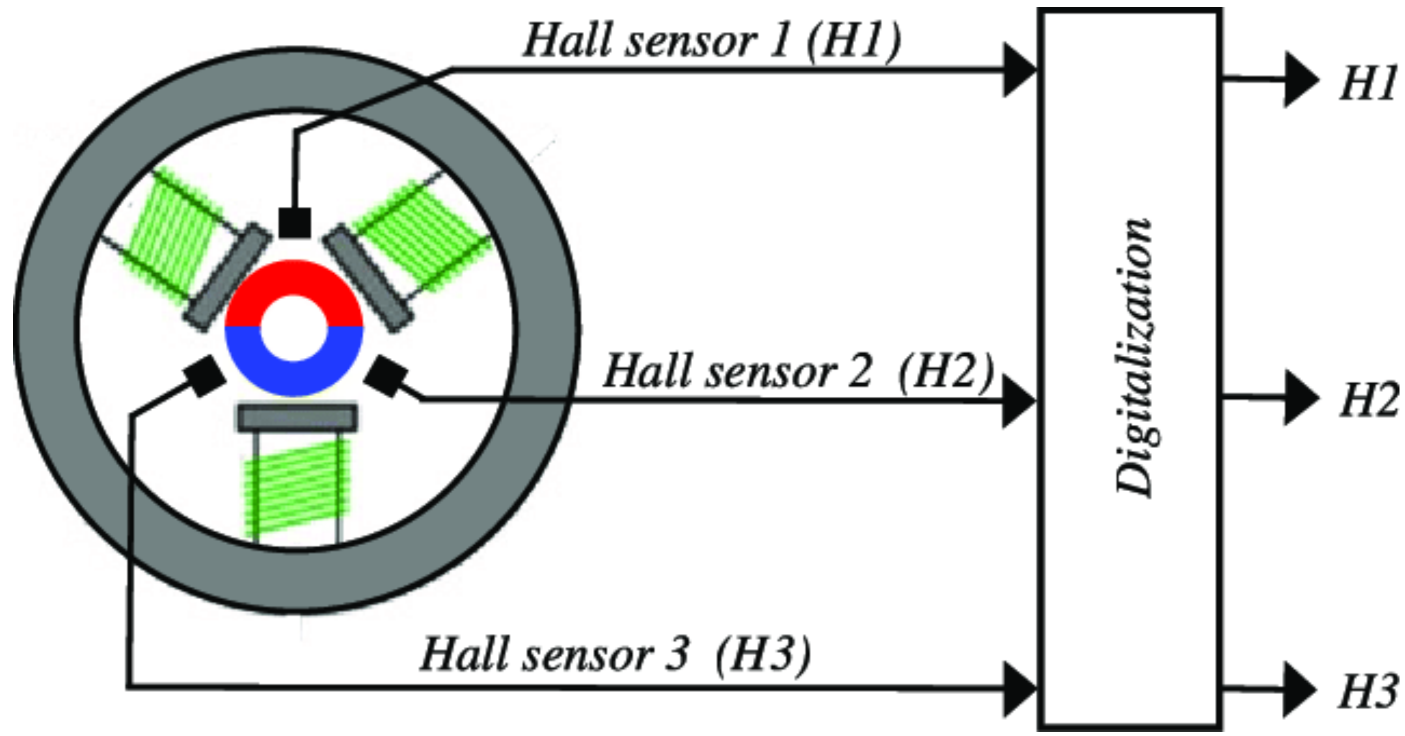
Calibration and signal processing allows to determine the three components of the original magnetic field



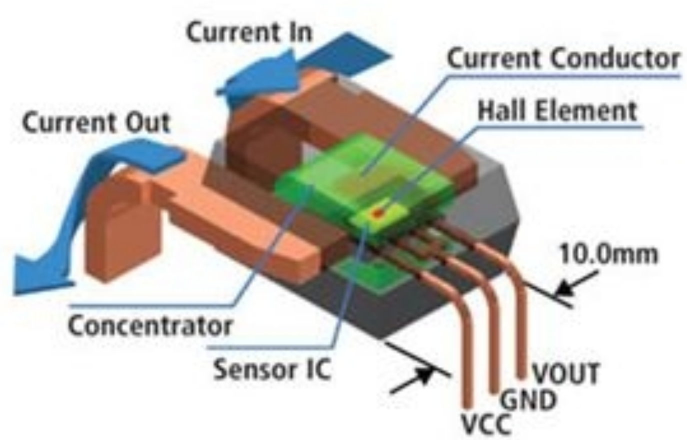
Sensing principles Hall sensors

Electronic compass

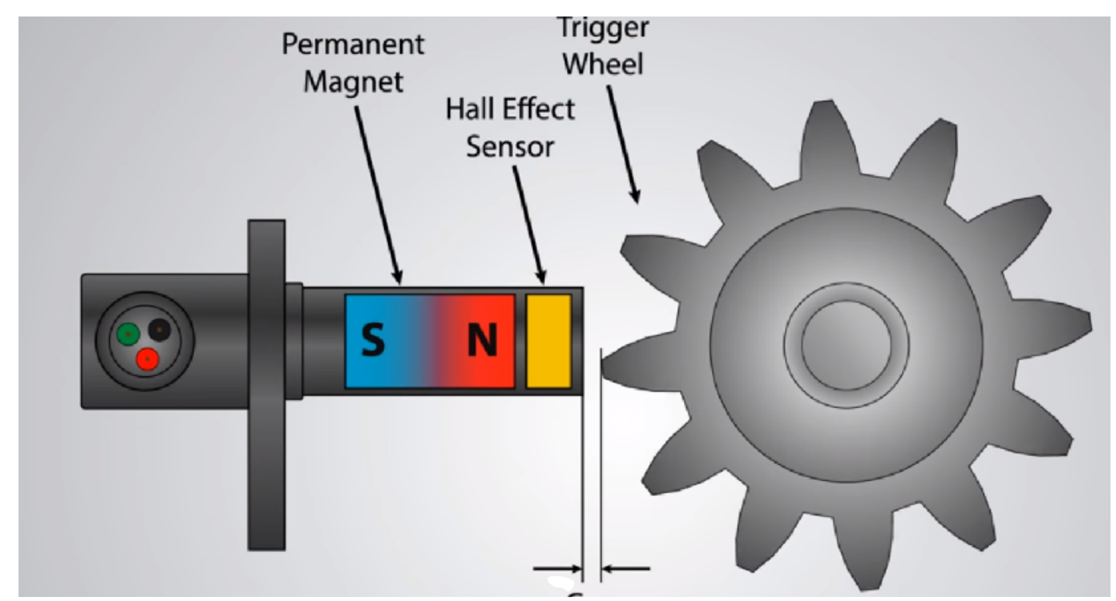
Commutation in bushless DC motors



Current measurement



Magnetic encoders



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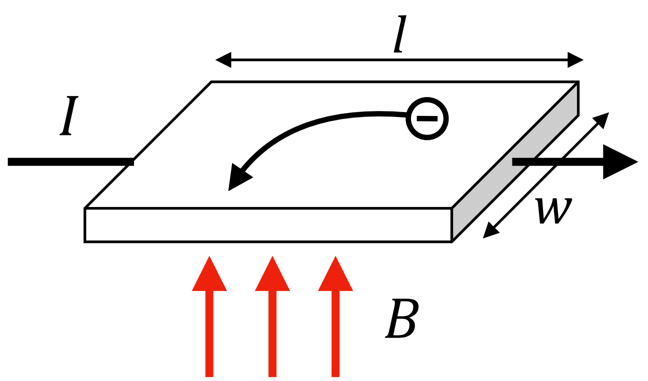
    ***d.* Magnetoresistance sensors: AMR, GMR, TMR.**
    e. Magnetoelastic sensors *(torque sensors, anti-shoplifting labels).*

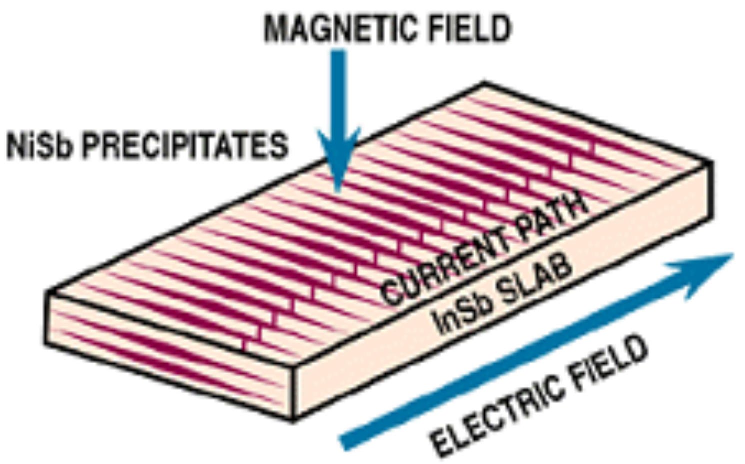
2. Sensing principles and examples
Magnetoresistance sensors

Classical Magnetoresistance:

Occurs in all conductors, but more evident in semiconductors. Same origin as Hall effect.



$$R(B) \propto (1 - 0.54\frac{l}{w})B^2$$



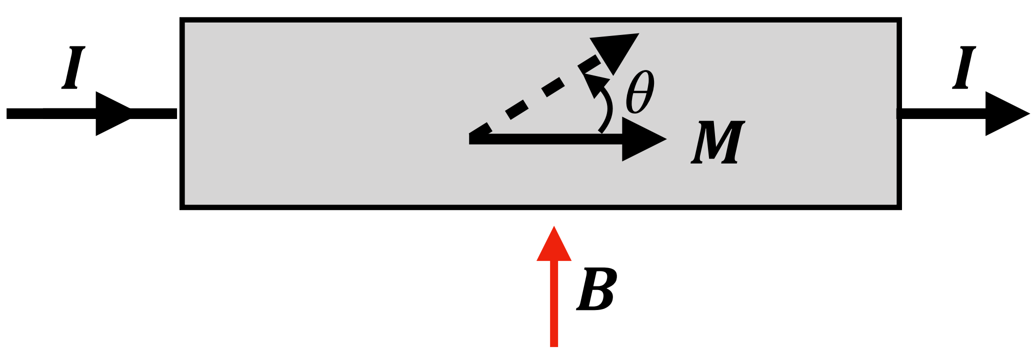
The magnetic field modifies the trajectories of the carriers, increasing the resistance

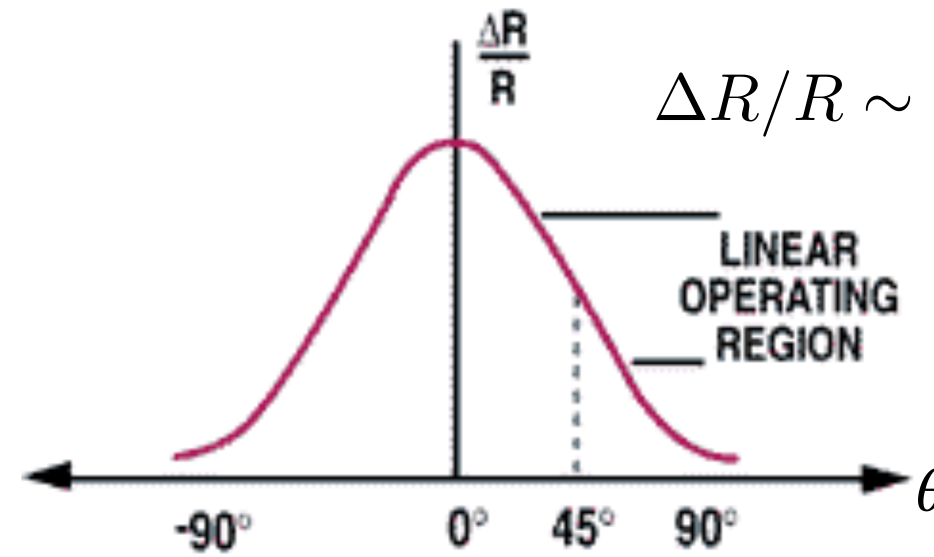
There is a geometry effect. Short and wide elements are preferred.

Feldplatte sensors, with traversal NiSb needles. Developed by Weiss (1966), comercialized by Siemens.

Anisotropic Magnetoresistance AMR:

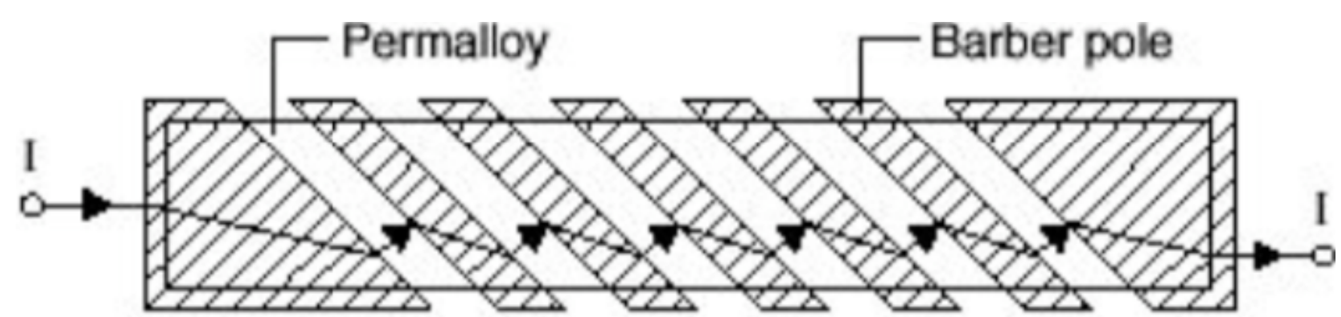
In ferromagnetic metals, the resistivity depends on the orientation of the magnetization with respect to the direction of the current.





$$\Delta R/R \sim 2-4\%$$

In soft materials, it is very sensitive to small magnetic fields.

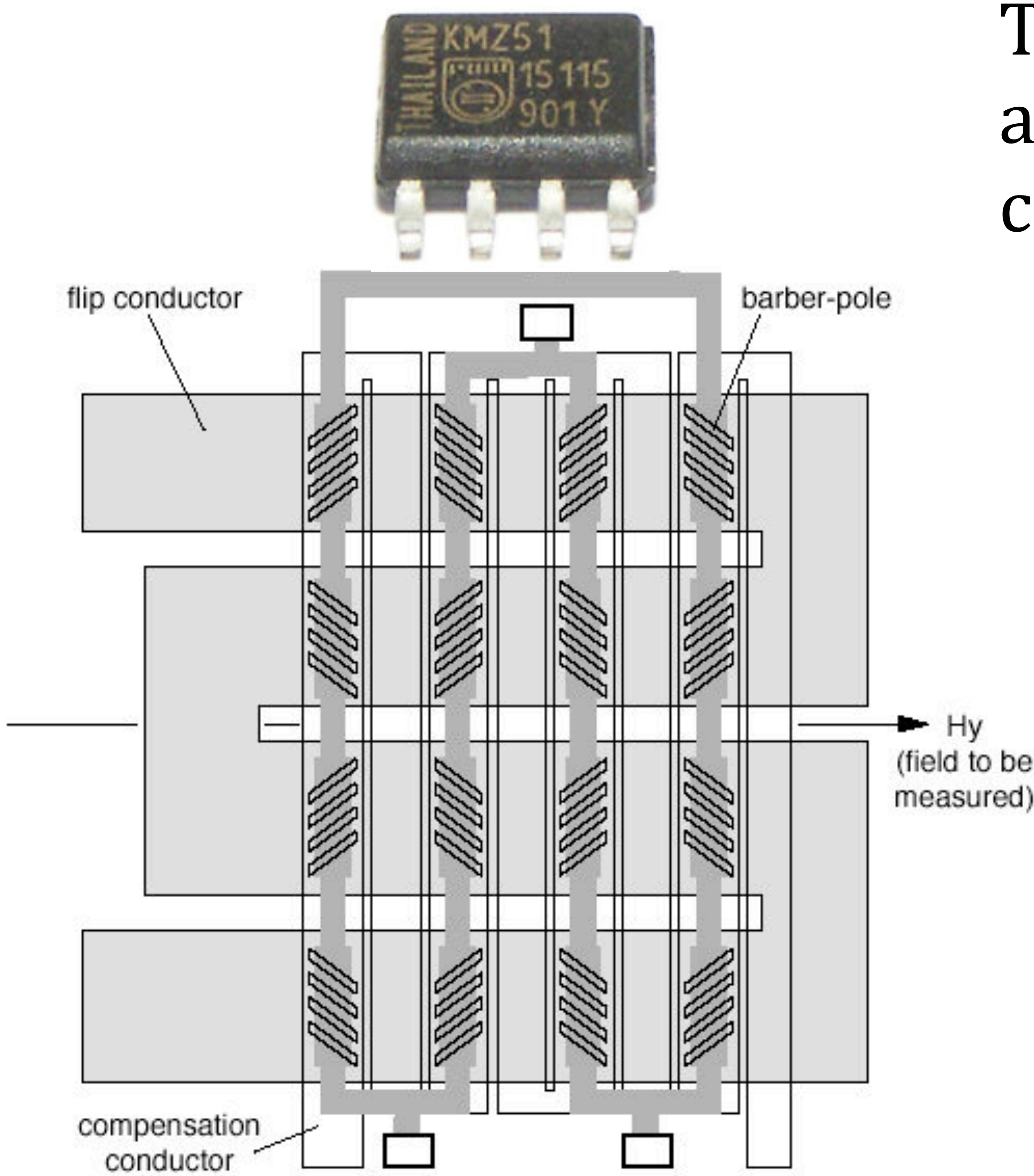


Usually made of Permalloy thin films, with a well defined magnetization direction.

"Barber-pole geometry to operate in the linear region.

C. Wang et al. IEEE Trans. Magn. **54** (2018) 2301103

AMR sensors are very sensible to small magnetic fields. They need additional circuitry for reseting to known state and compensation.



Philips KMZ51 Layout

They are very extended in industrial applications as electronic compasses, current sensors, etc.

Compass sensor comparison

	Hall*	Fluxgate	AMR
sensitivity	small	high	medium-high
range	medium	large	Small-medium
size	small	large	small-medium
price	low	high	medium

* with field concentrator

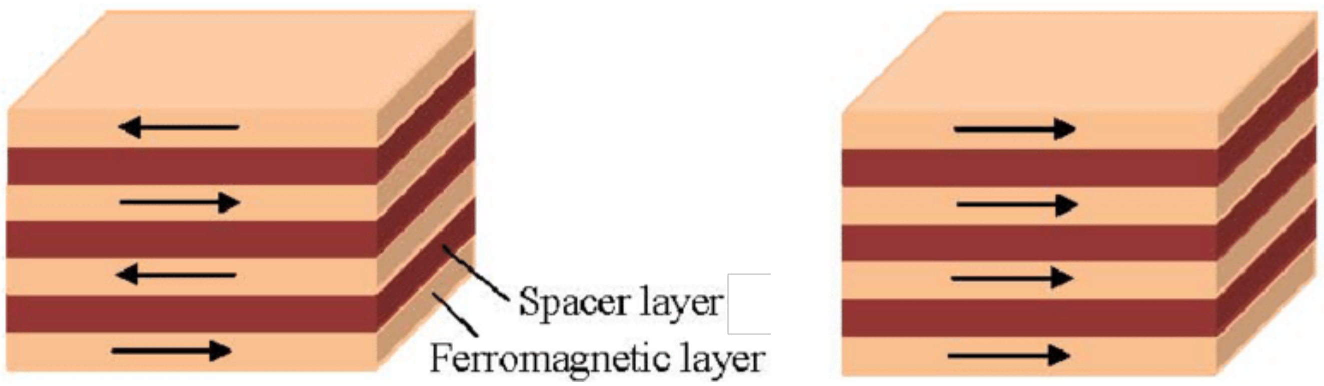
Extensive information on AMRs:
S. Tumansky, *Thin film magnetoresistive sensors*, IoP Publishing, 2001.

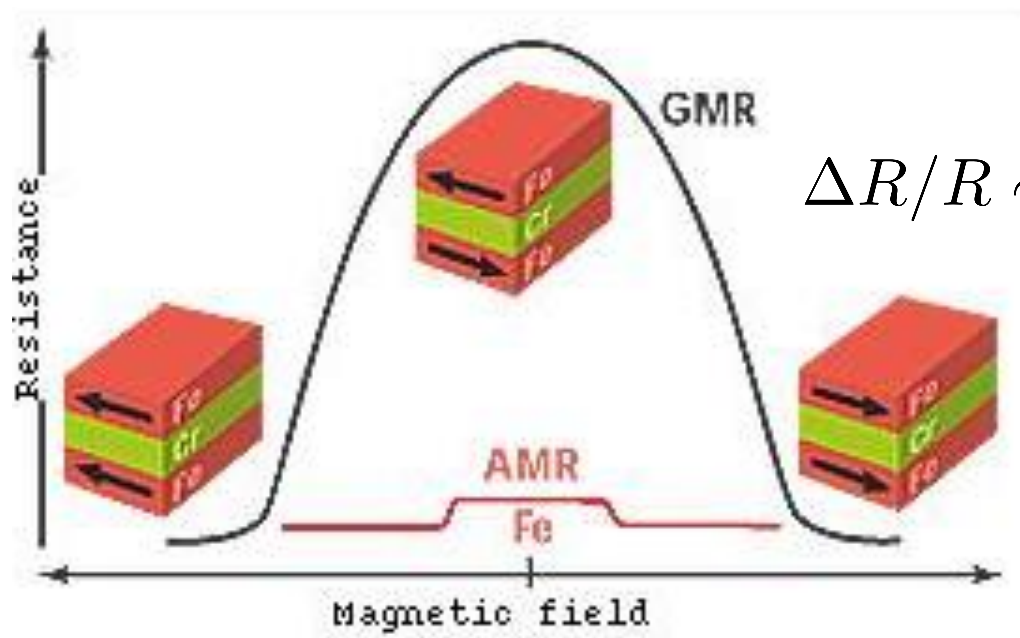
Giant Magnetoresistance:

Origin of spintronics. 2007 Nobel prize.

Magnetic/non-Magnetic multilayers.

$H = 0$ $H = H_s$





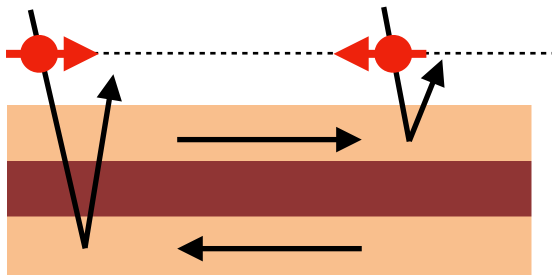
source: fz-juelich.de

$$\Delta R/R \sim 100\%$$

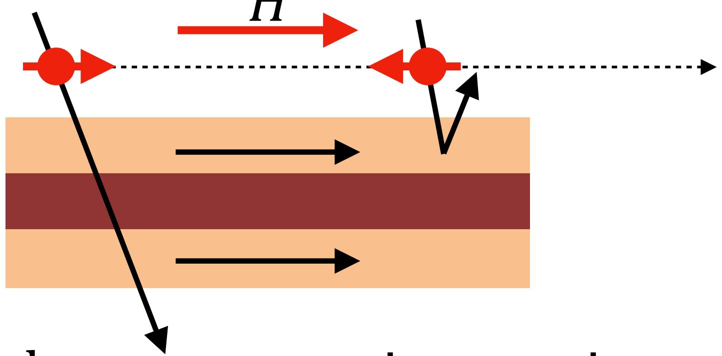
Albert Fert

Peter Grünberg

Two currents model



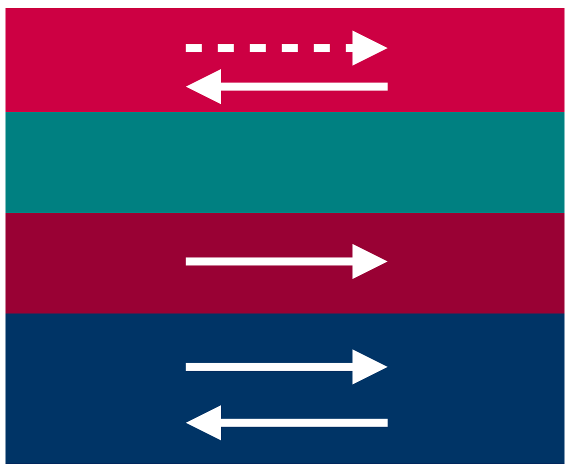
all electrons experience spin scattering



no all electrons experience spin scattering

Spin valves:

First evolution of basic GMR



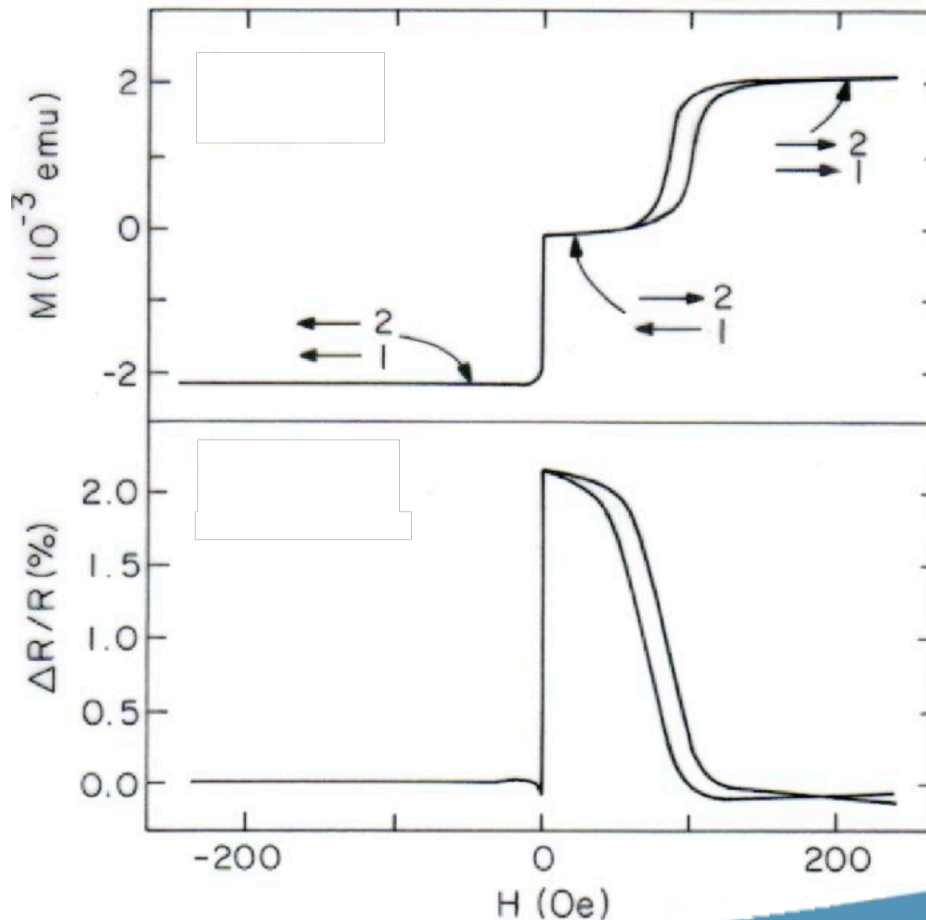
Free layer

non-magnetic spacer

pinned layer

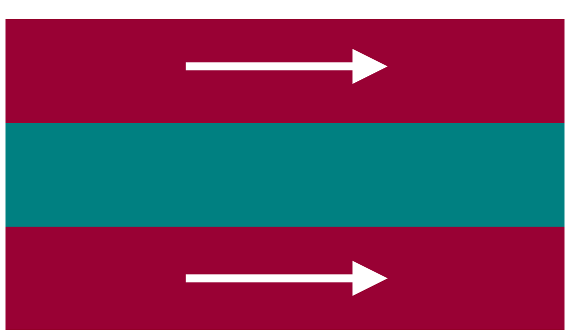
Antiferromagnetic

The free layer magnetization rotates in small field



Tunneling Magnetoresistance (TMR):

Actual GMR devices



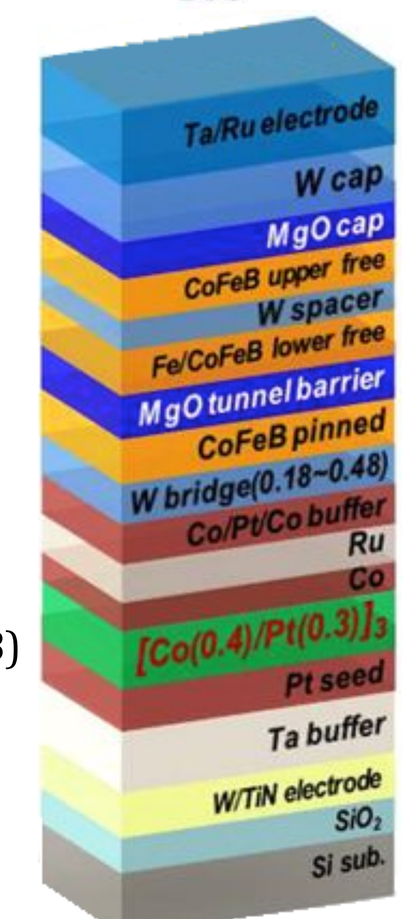
ferromagnetic

insulator

ferromagnetic

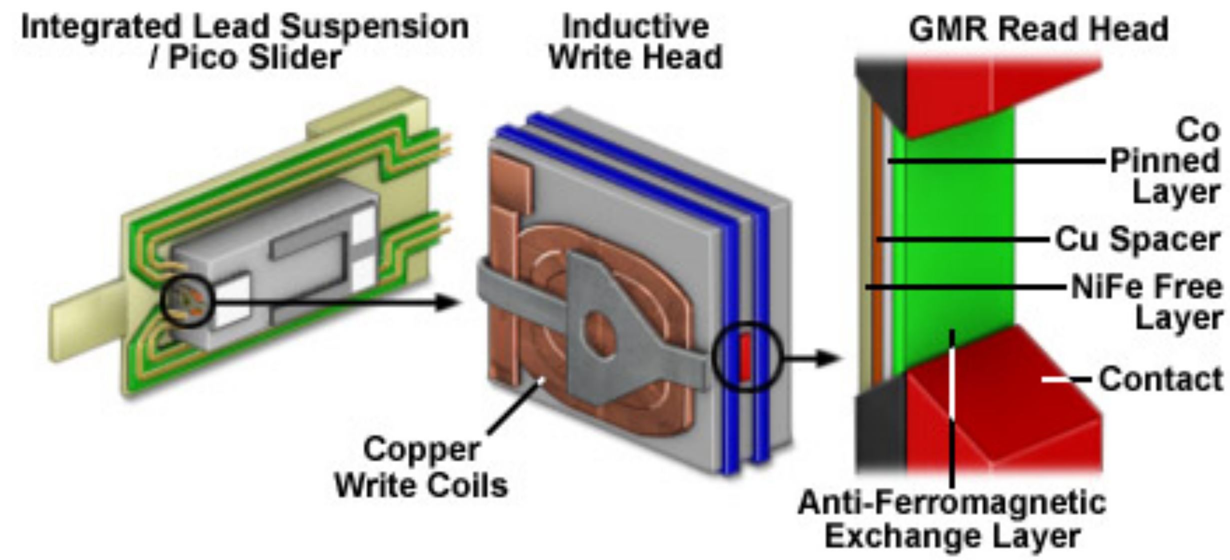
Magnetic Tunnel Junctions (MTJ) are composed of multiple layers

J-Y. Choi, Scientific Reports 8, 2139 (2018)

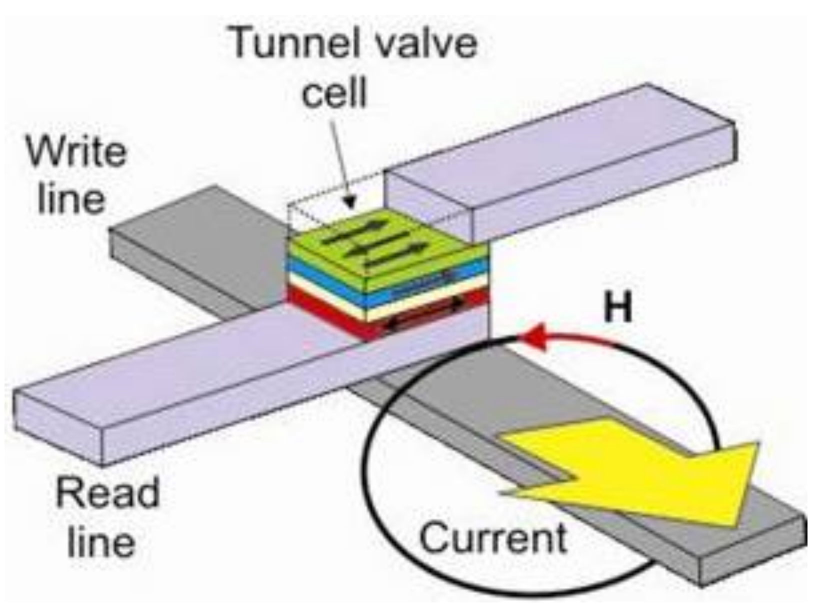


GMR, especially MTJ are driving the progress in many applications

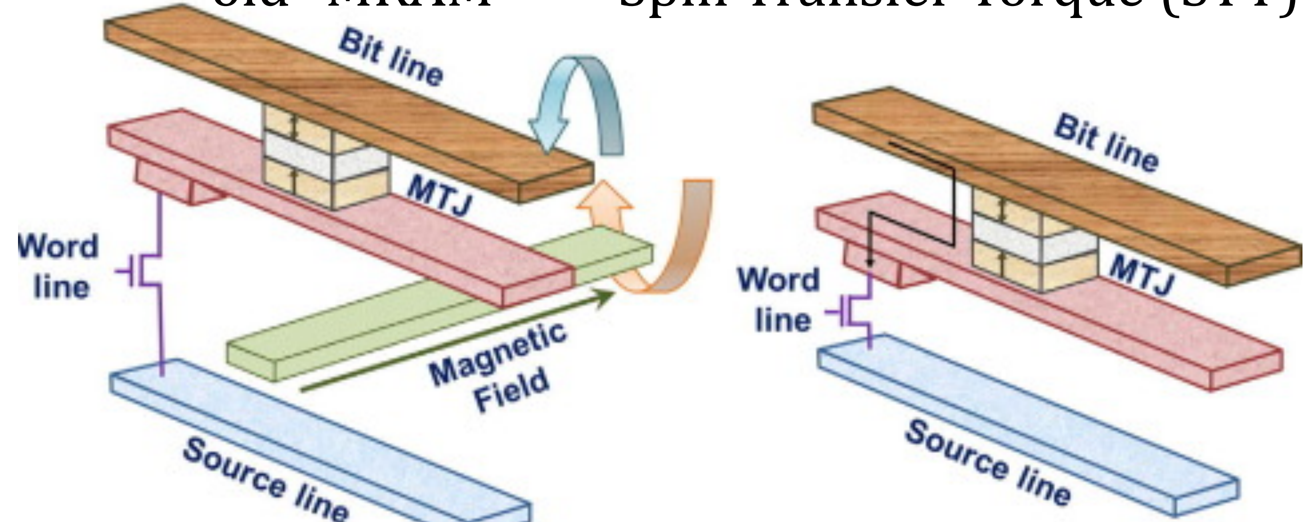
Read heads in hard discs



Magnetic RAM (MRAM)



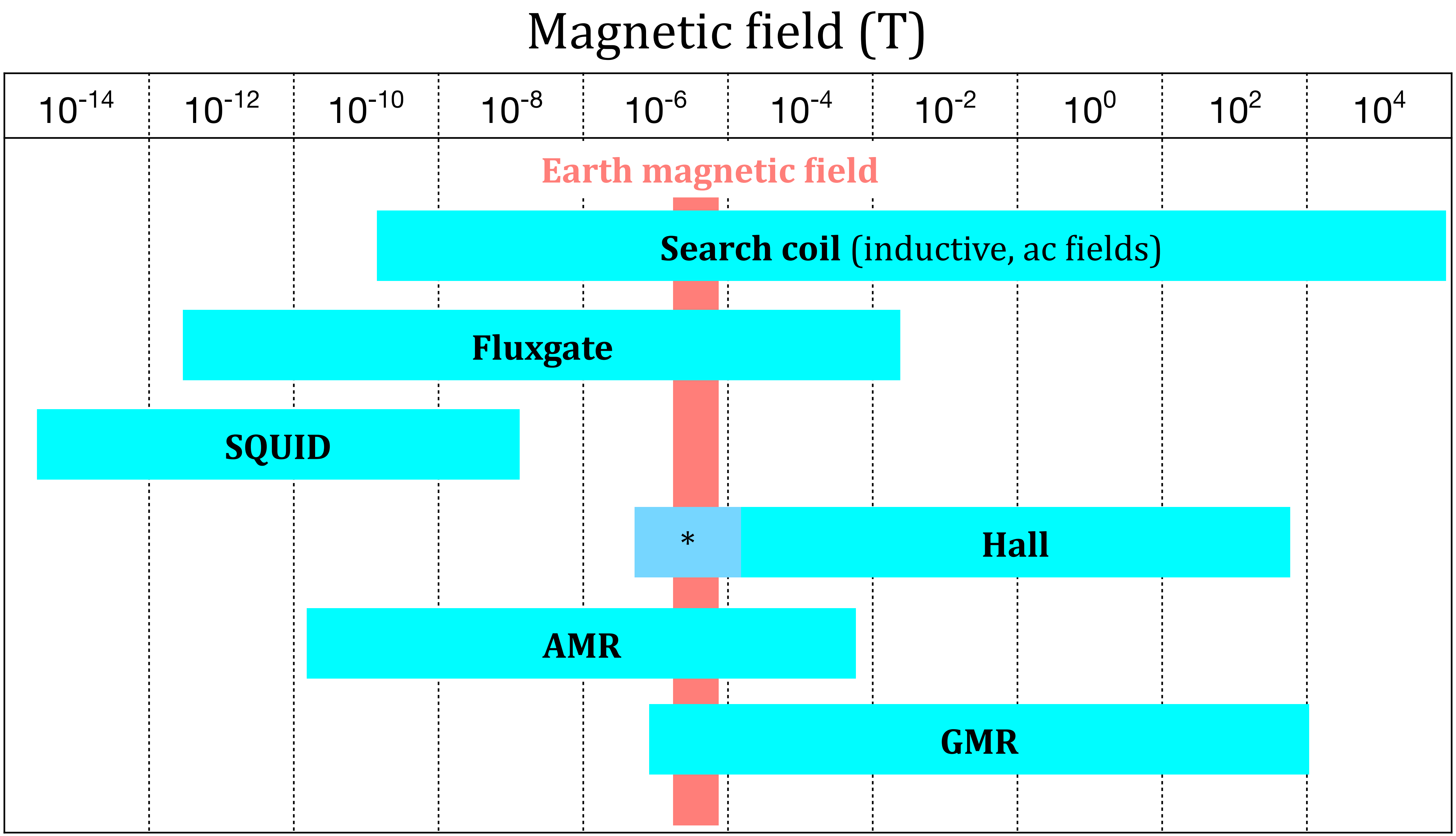
"old" MRAM Spin Transfer Torque (STT) MRAM



S. Bhatti, Materials Today **20** (2017) 530

source: www-ssrl.slac.stanford.edu

Comparative chart of magnetic field sensors



* With flux concentrator

Range limits are indicative

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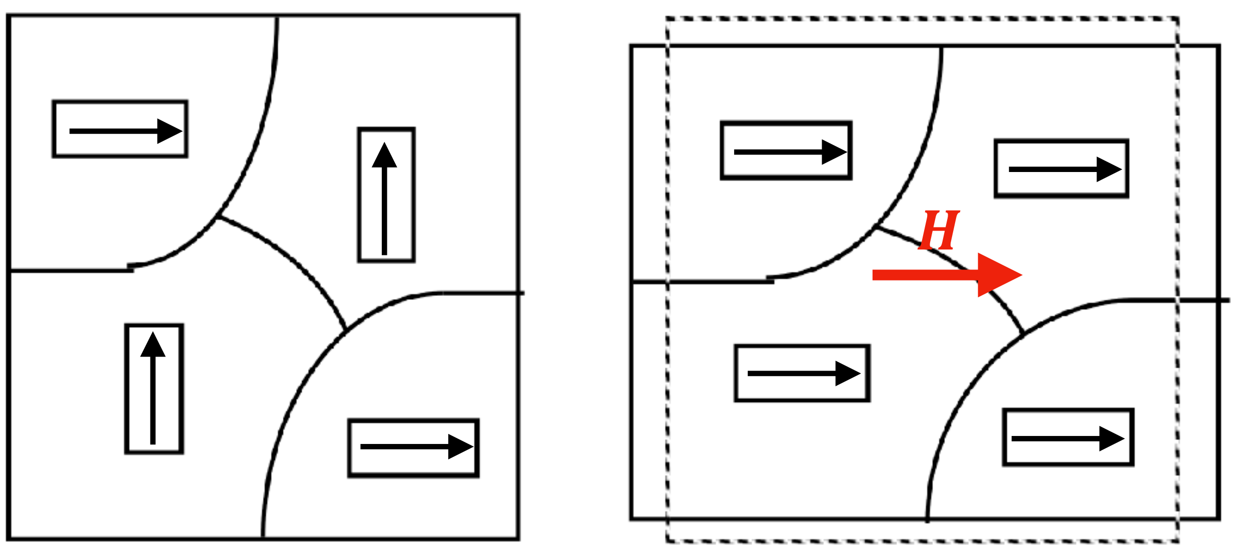
***e.* Magnetoelastic sensors** *(torque sensors, anti-shoplifting labels).*

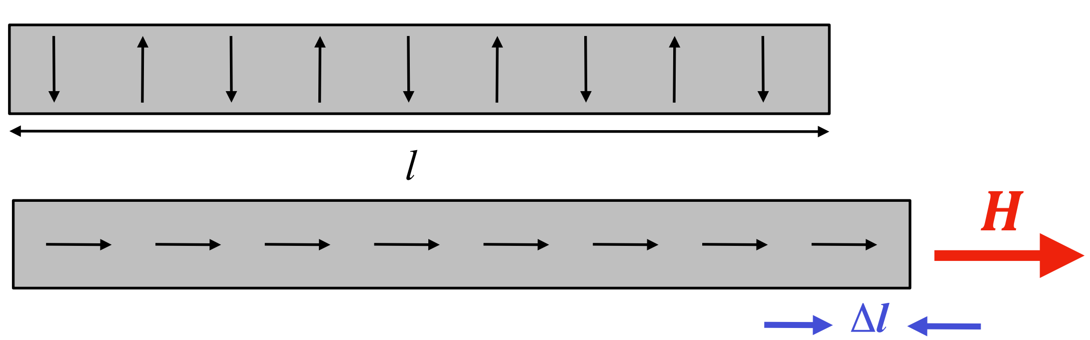
2. Sensing principles and examples
Magnetoelastic sensors

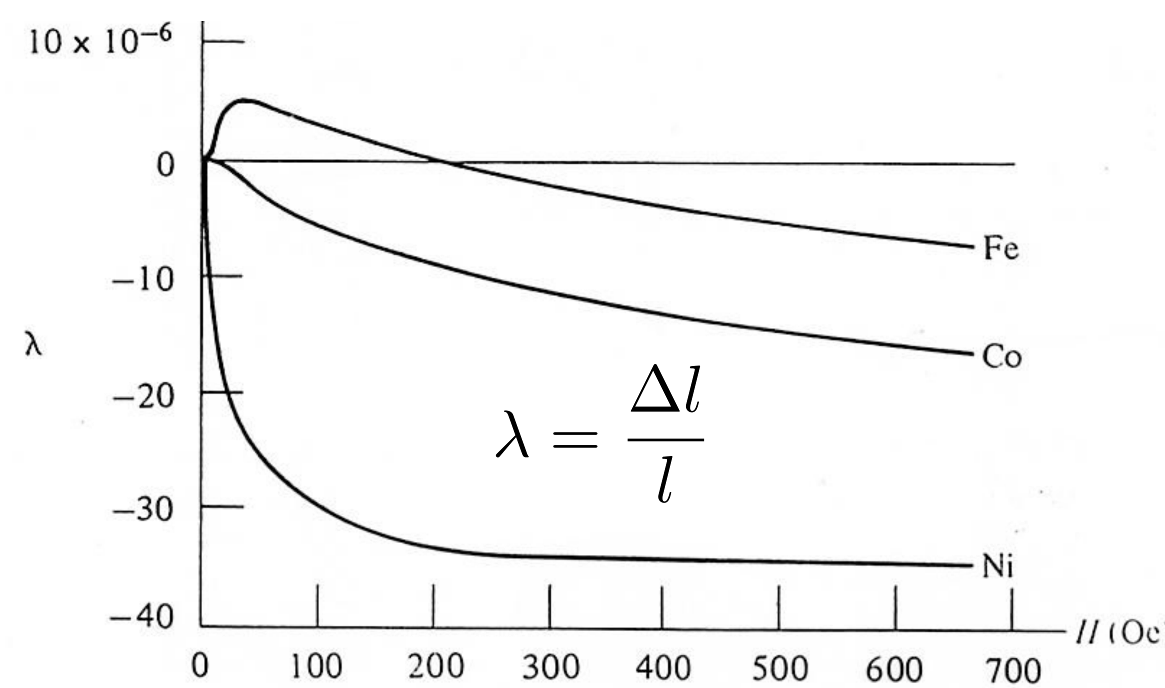
Example of magnetic sensors based on coupled properties, in this case, elastic and magnetic.

Magnetostriction:

change in length in the direction of the magnetization





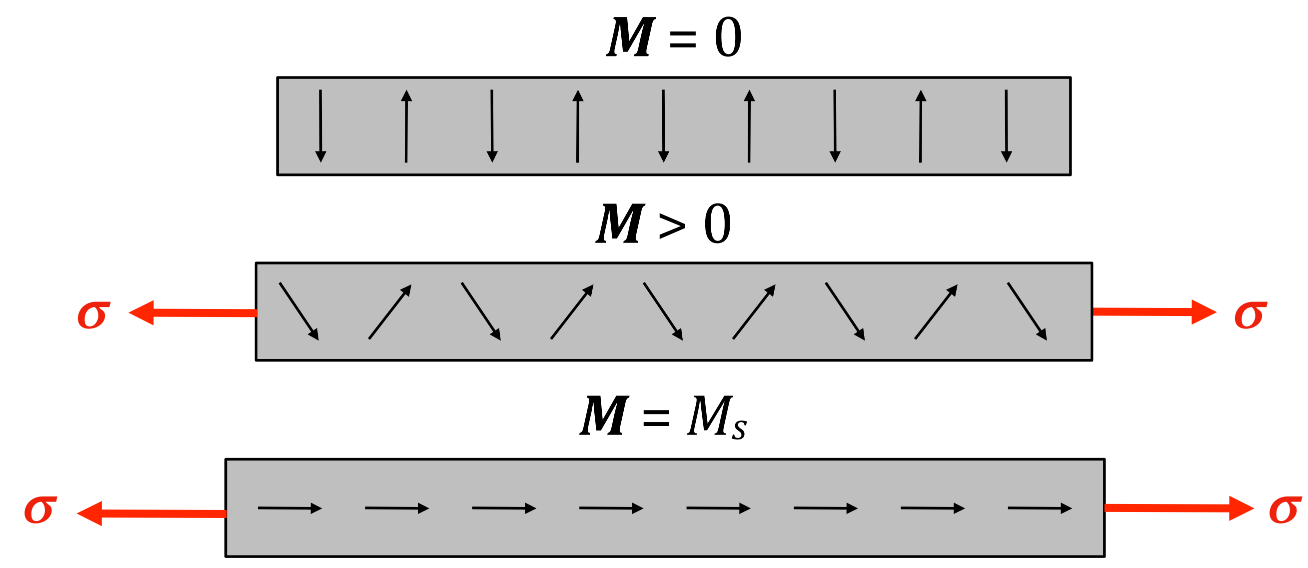


Important applications in actuators

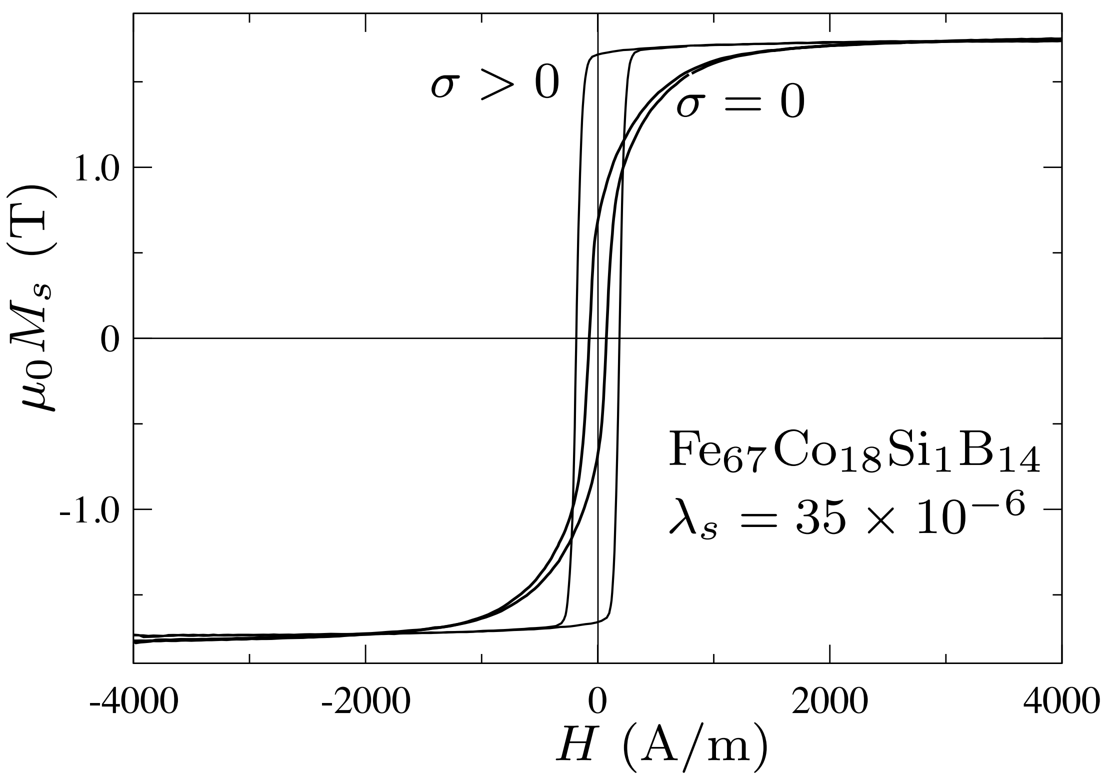
Magnetoelasticity:

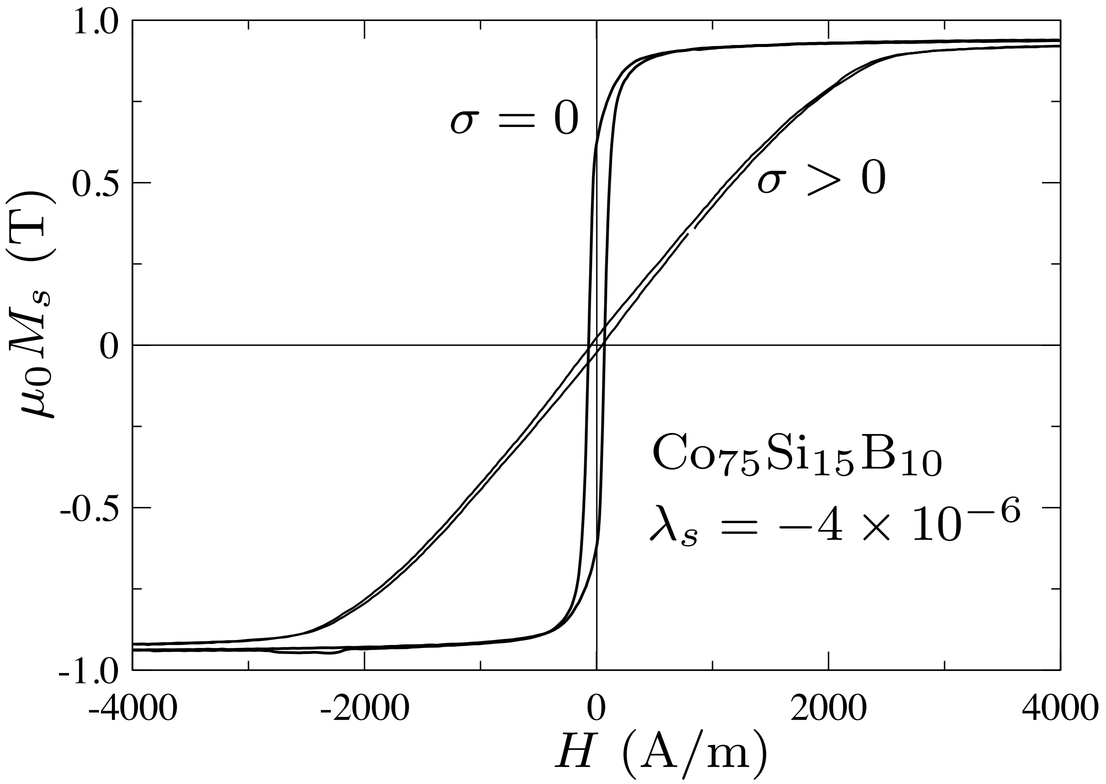
Inverse phenomenon:

change in magnetization when strained (under a stress).

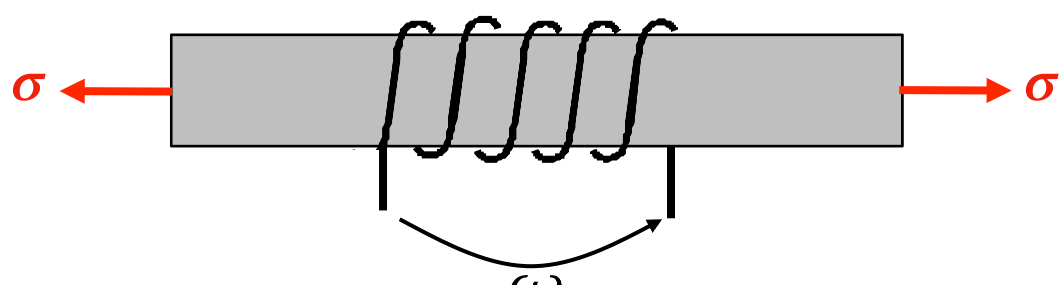


Important consequences in the magnetization process.

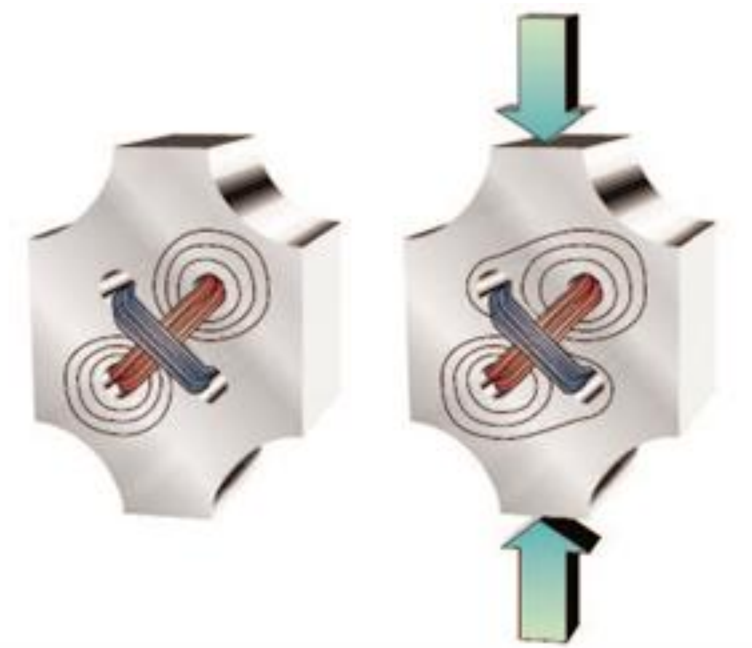




Direct application in sensors

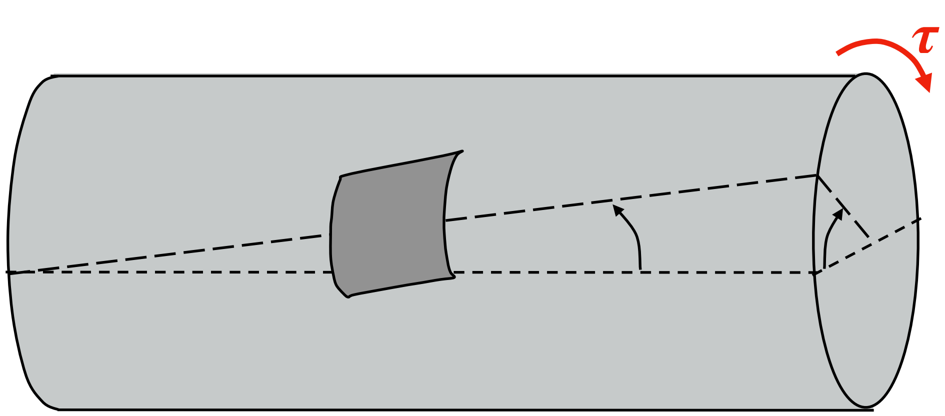


signal induced due to magnetization changes

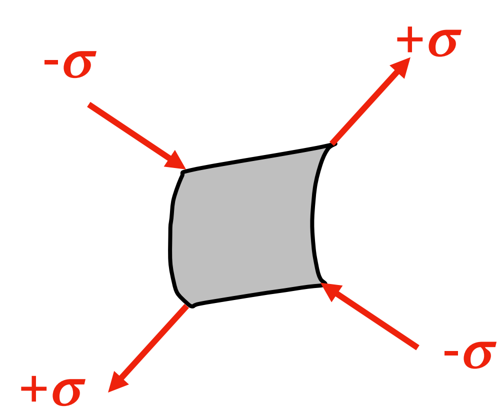


Pressductor force sensor (ABB)

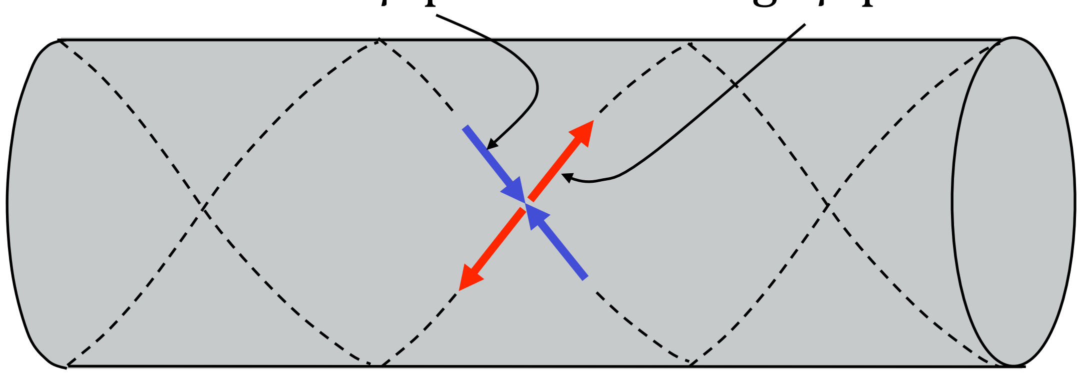
Especial relevance in *torque sensors* for rotating shafts because of non-contact nature



The torsion deforms the surface

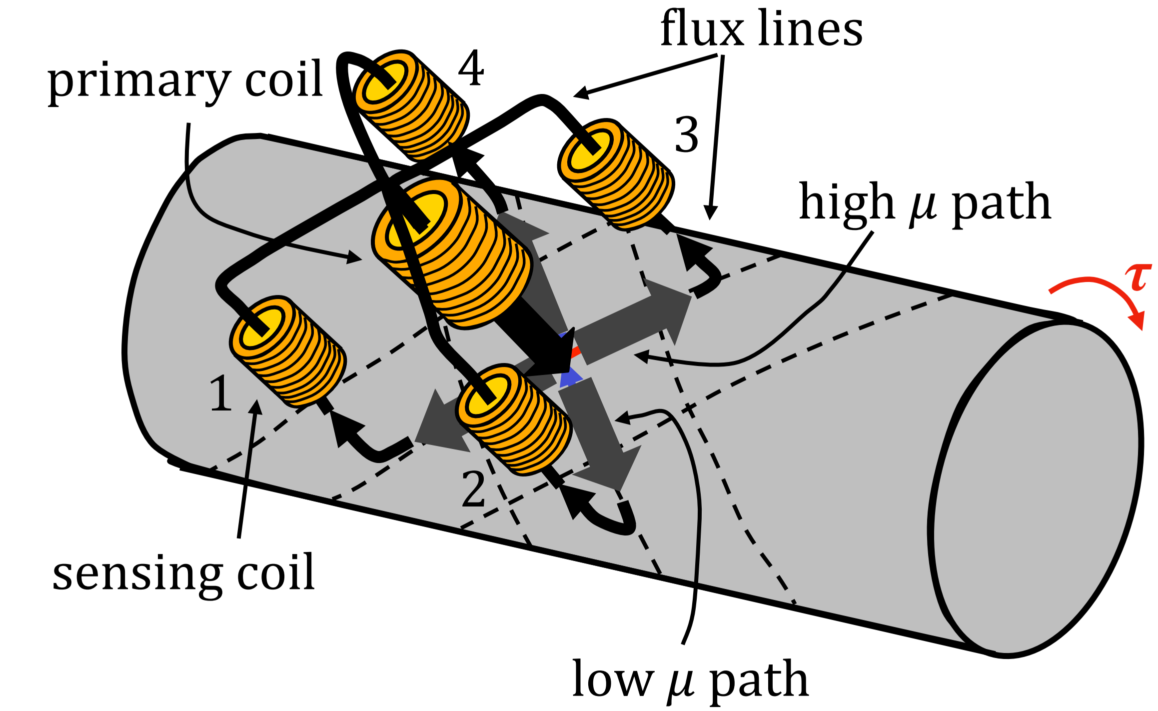


with strains of opposite sign at 45°



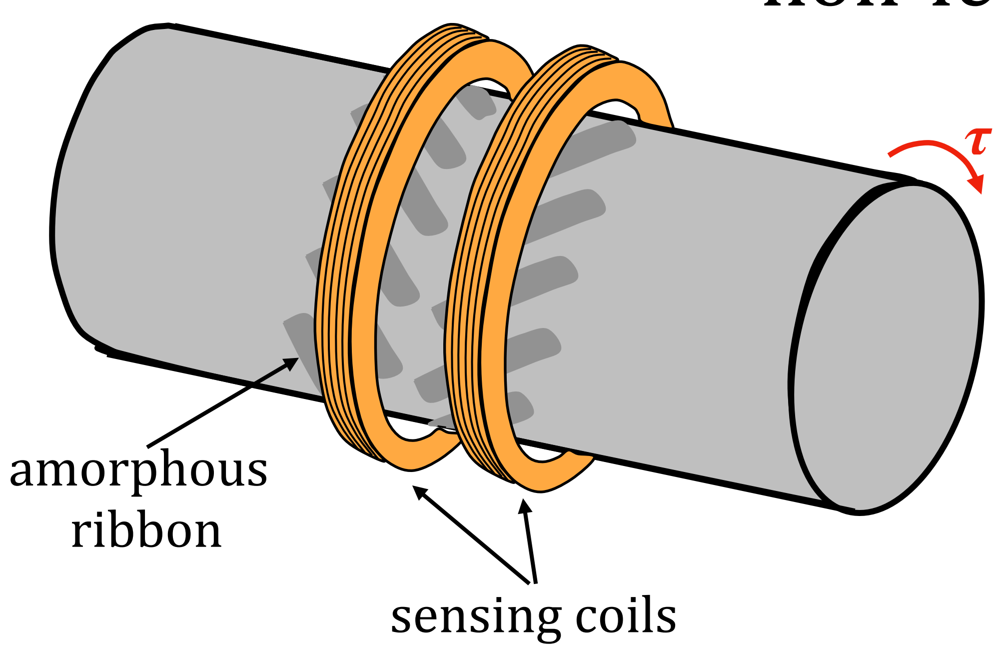
causing the permeability to change differentially

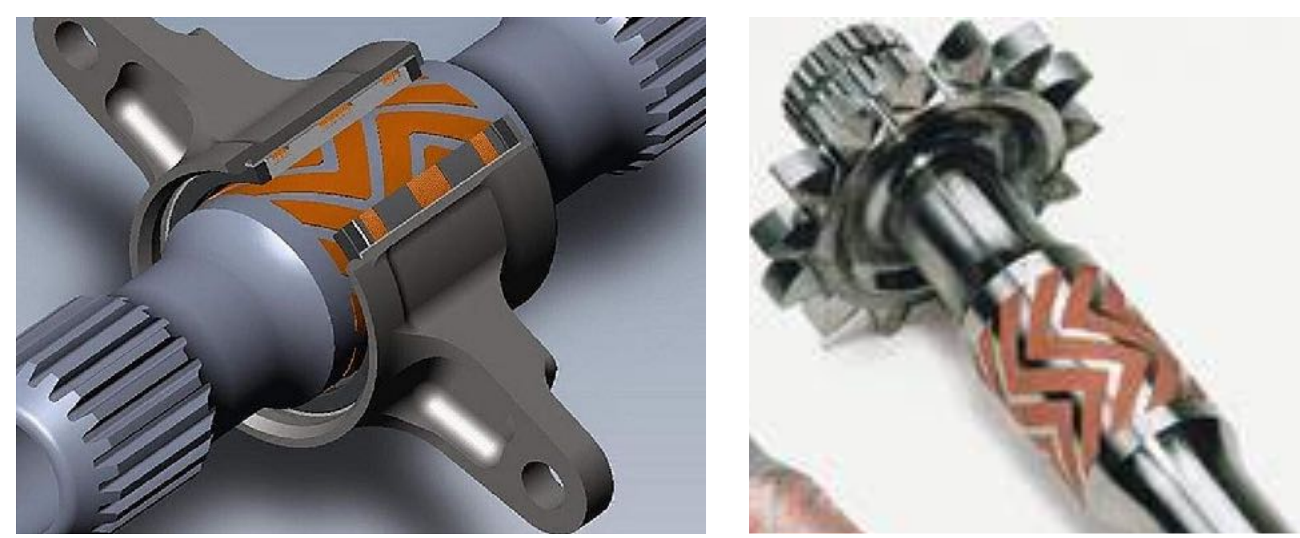
ferromagnetic shaft



Torductor (ABB) for propeller shafts in ships

non-ferromagnetic shaft



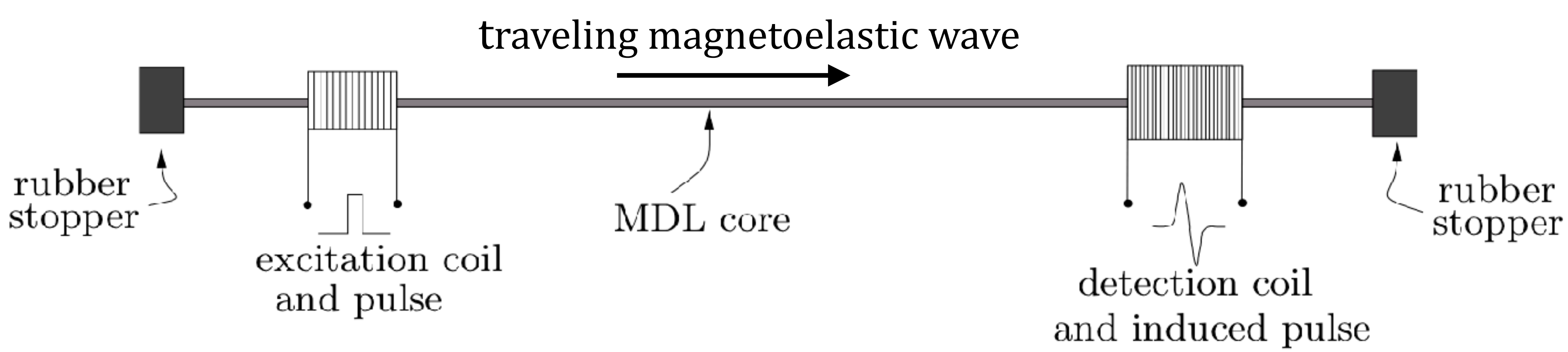


Torductor-S (ABB) for high end motorsport (Moto GP and F1)

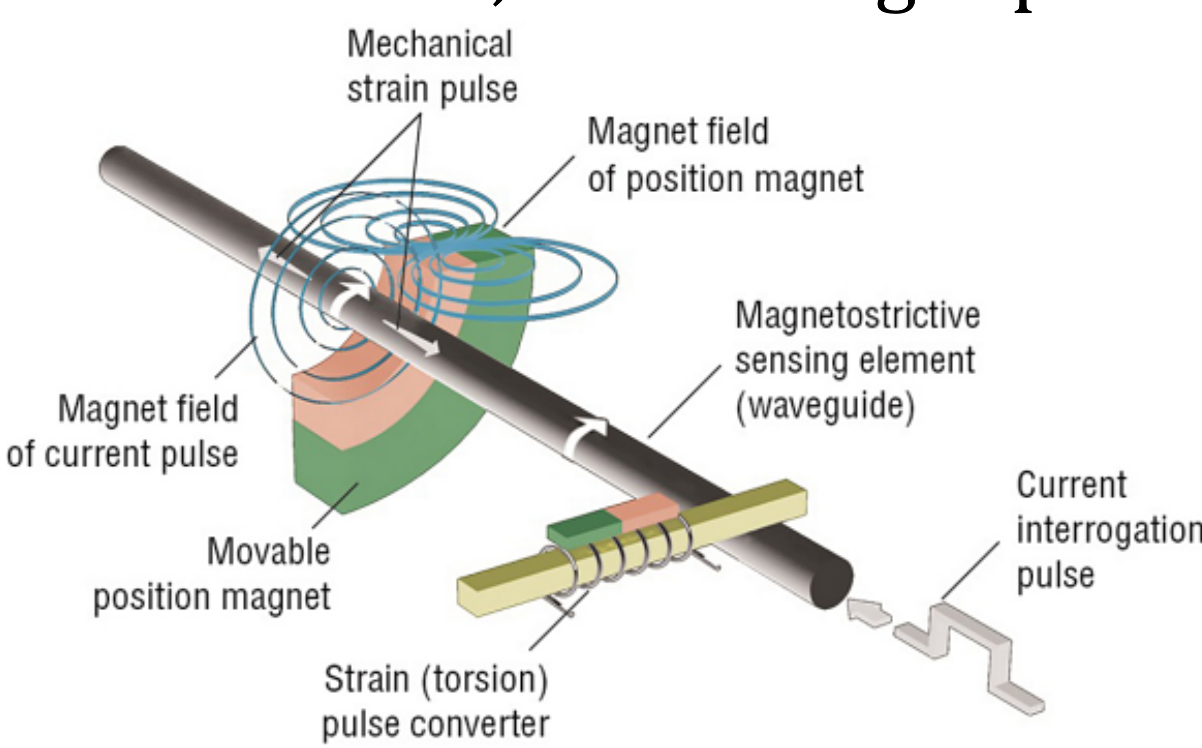
Magnetostrictive delay line:

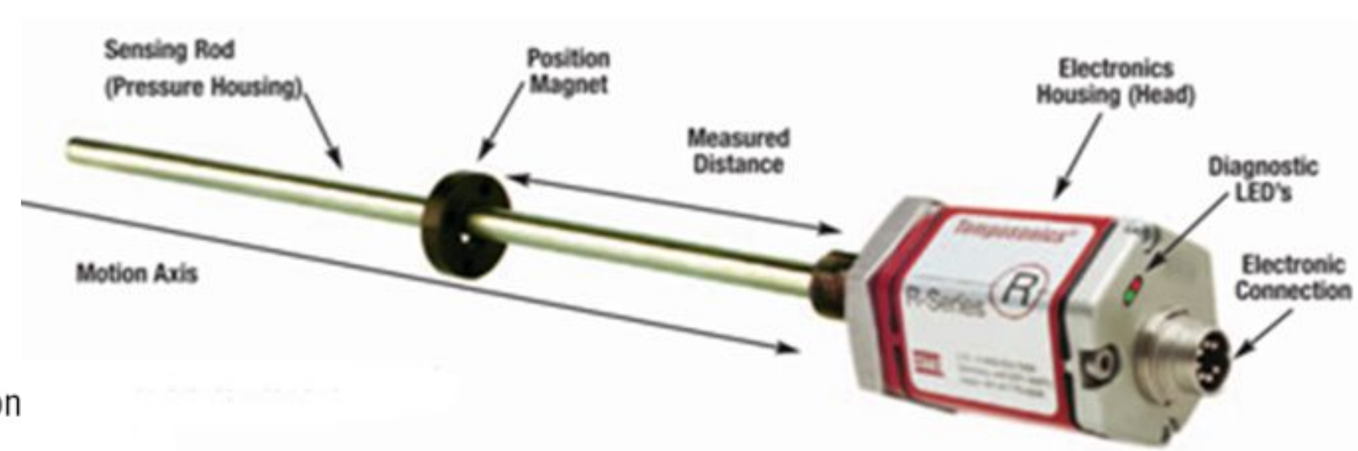
Strain waves in solids propagate at sound velocity.

Magnetostriction couples strain to magnetization producing the propagation of *magnetoelastic waves*.



Frictionless, time of flight position sensors



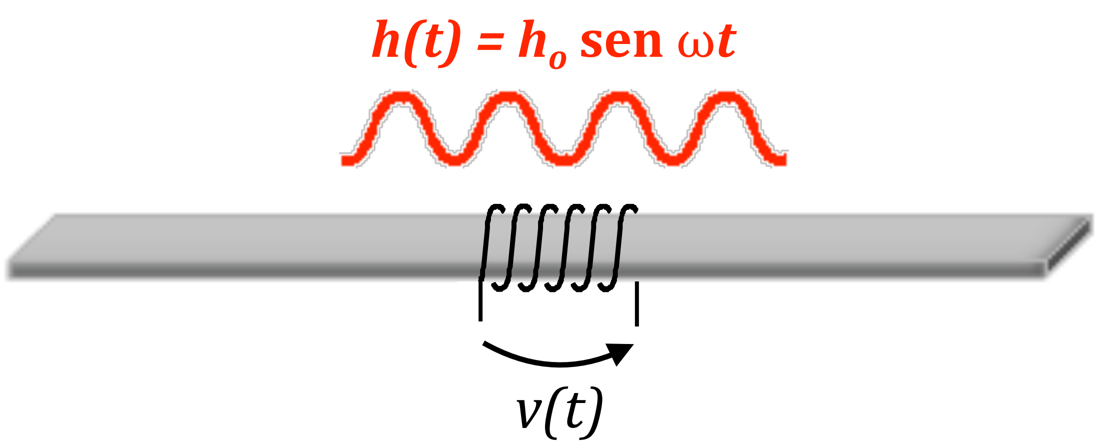


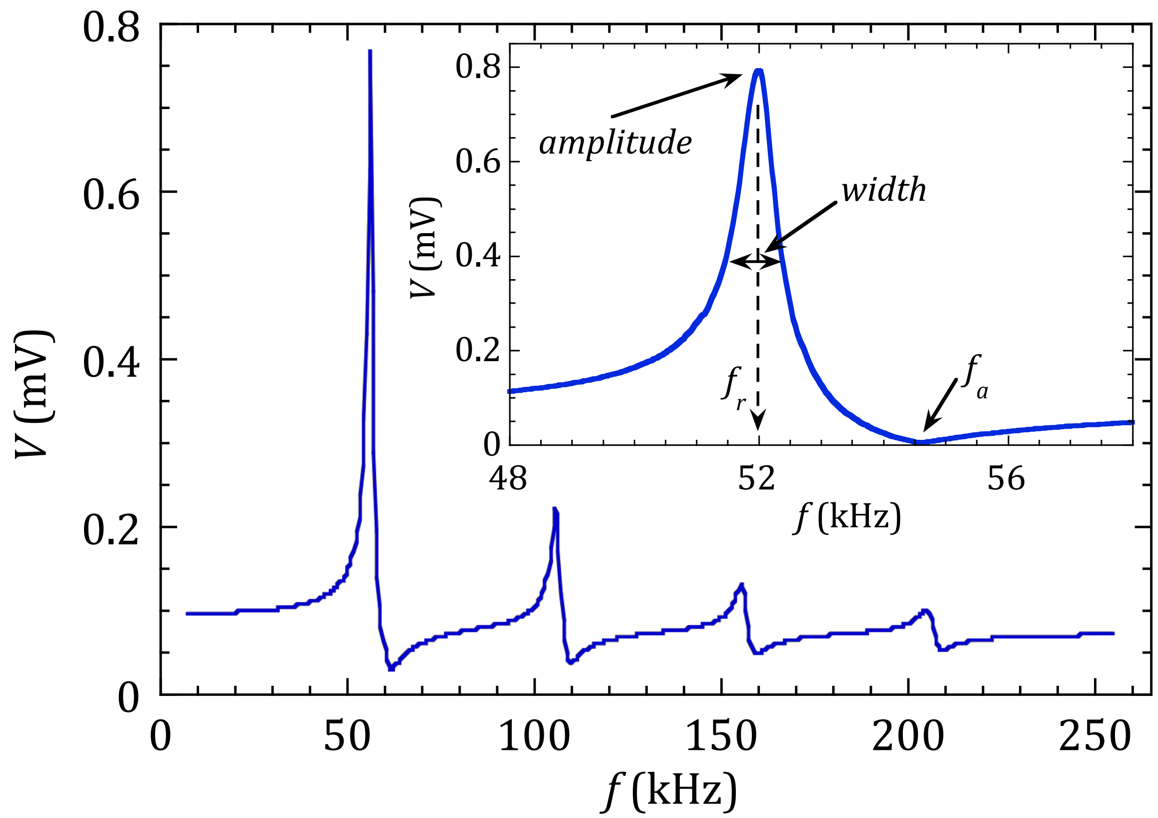
MTS.com *temposonic* position sensors

Magnetoelastic resonance

Magnetostriction makes materials to vibrate in alternate fields

(it produces the hum of electrical transformers)





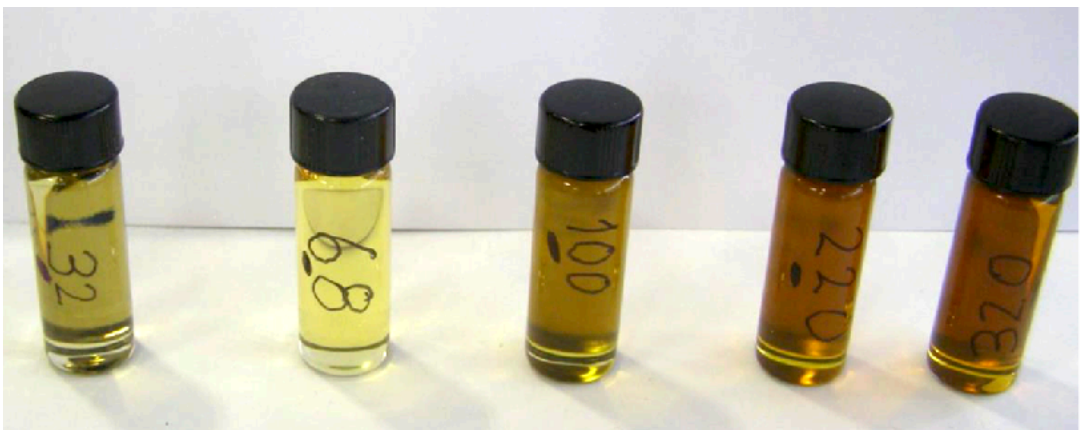
$$\omega_n = n\pi \frac{\sqrt{E/\rho}}{l}$$

E: Youngs modulus; *ρ*: density; *l*: length

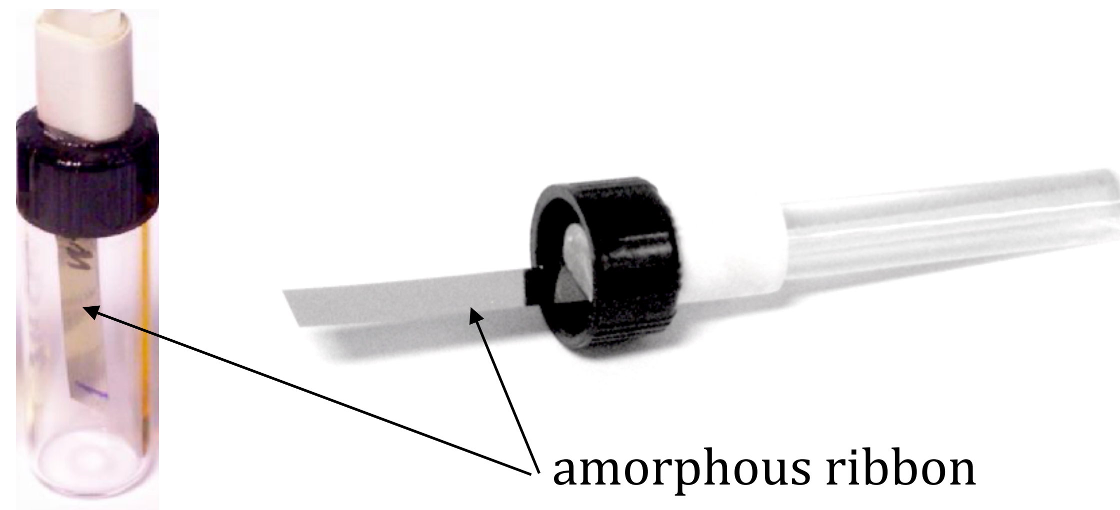
When the wavelength matches the length of the sample, standing waves builds up, and resonance takes place.

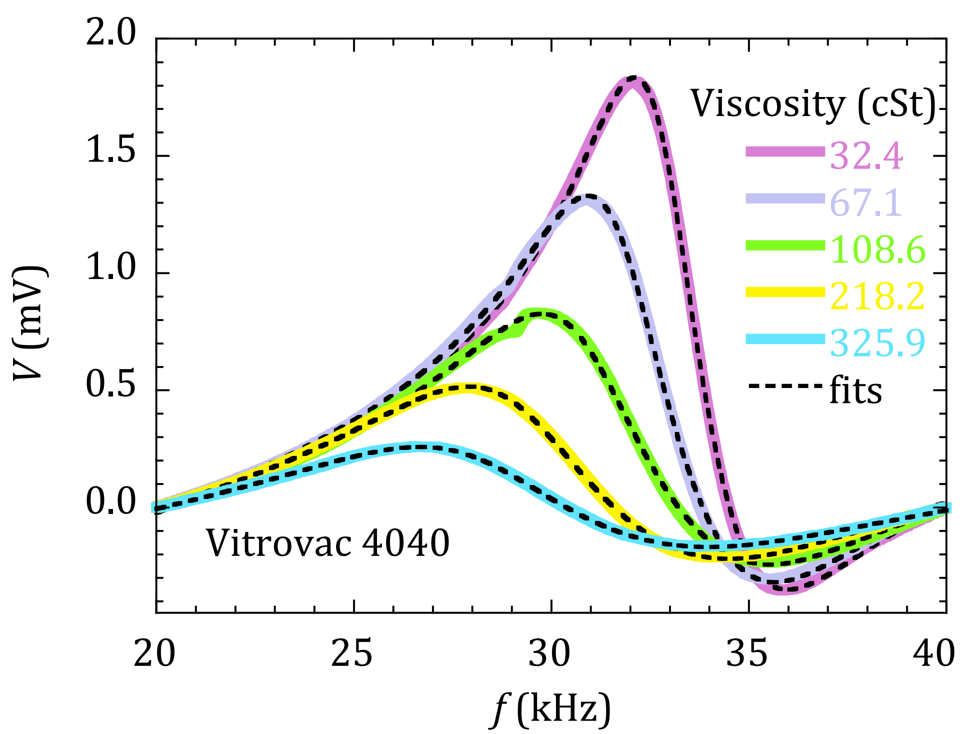
Oil *viscosity sensor:*

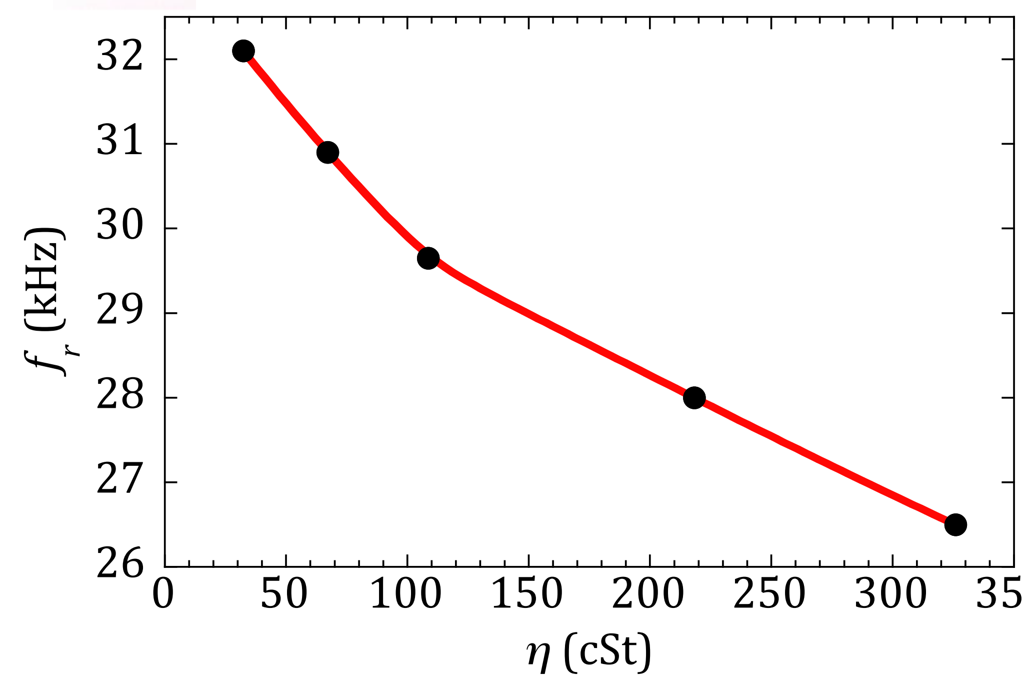
External factors modify the resonance. For example, the viscosity of the medium in which the sample oscillates.



lubricant oils with different viscosities

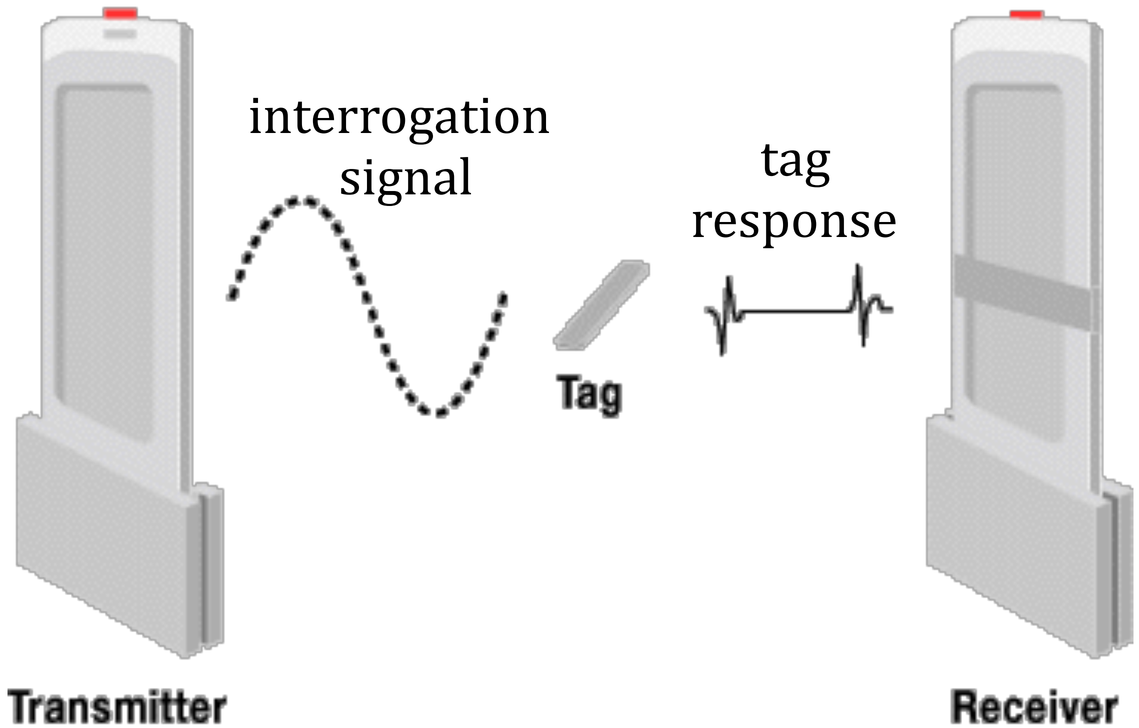






I. Bravo *et al.* IEEE Trans. Magn. **55** (2019) 4001105.

Anti-shoplifting labels:



Electronic article surveillance systems

Requisites:

- simple activation - deactivation of labels
- high sensibility (low amplitude signals)
- low price
- robust detection, no false alarms.

Magneto-acoustic labels are based in

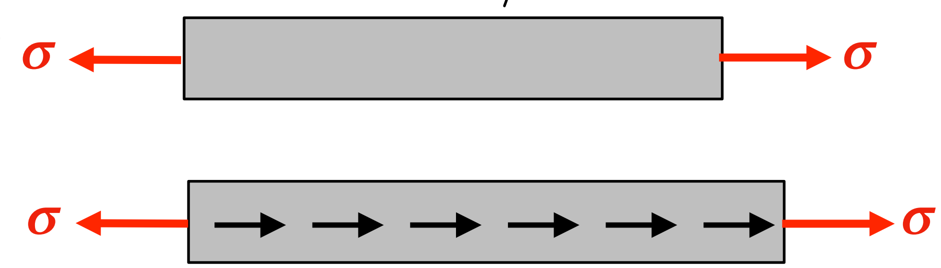
- magnetoelastic resonance
- ΔE effect

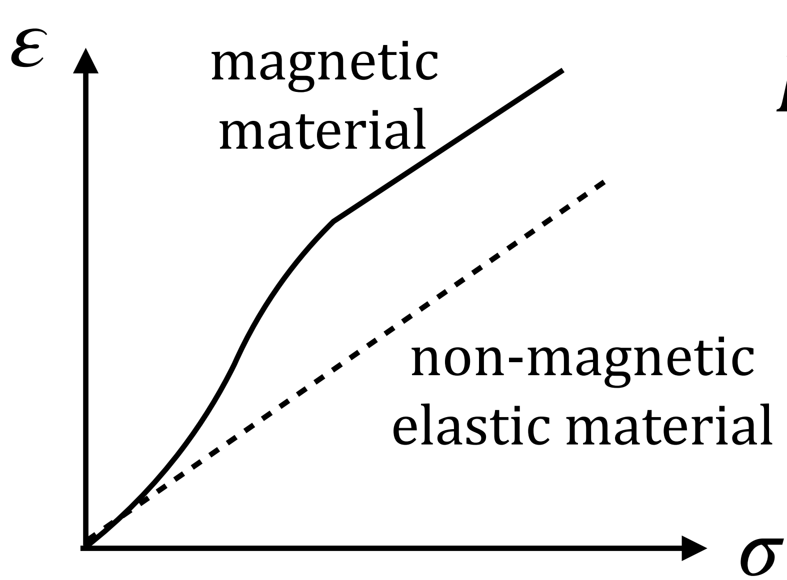
ΔE effect

Young's modulus *E* relates stress and strain

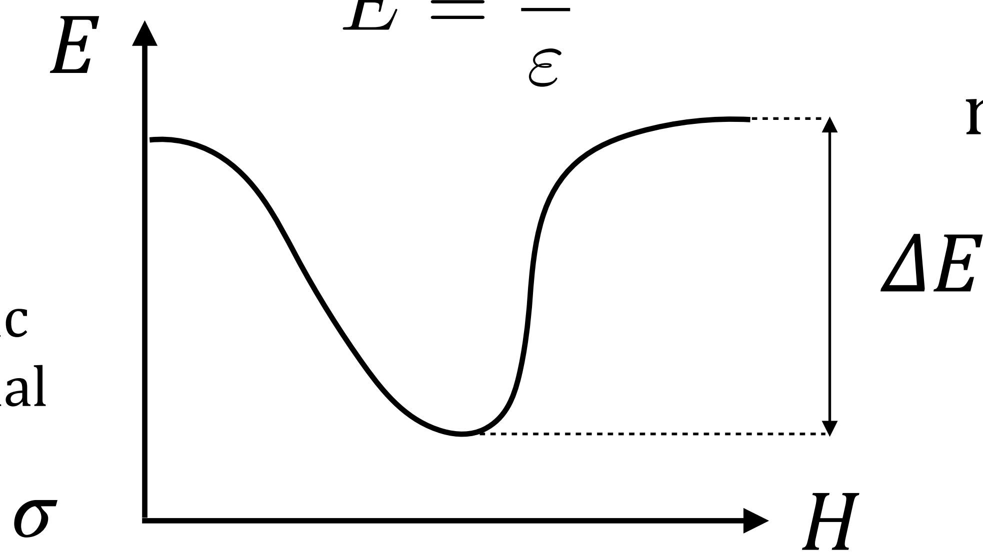
In a ferromagnetic material, magnetostriction imposes an additional strain

$$\varepsilon = \Delta l / l$$





$$E = \frac{\sigma}{\varepsilon}$$

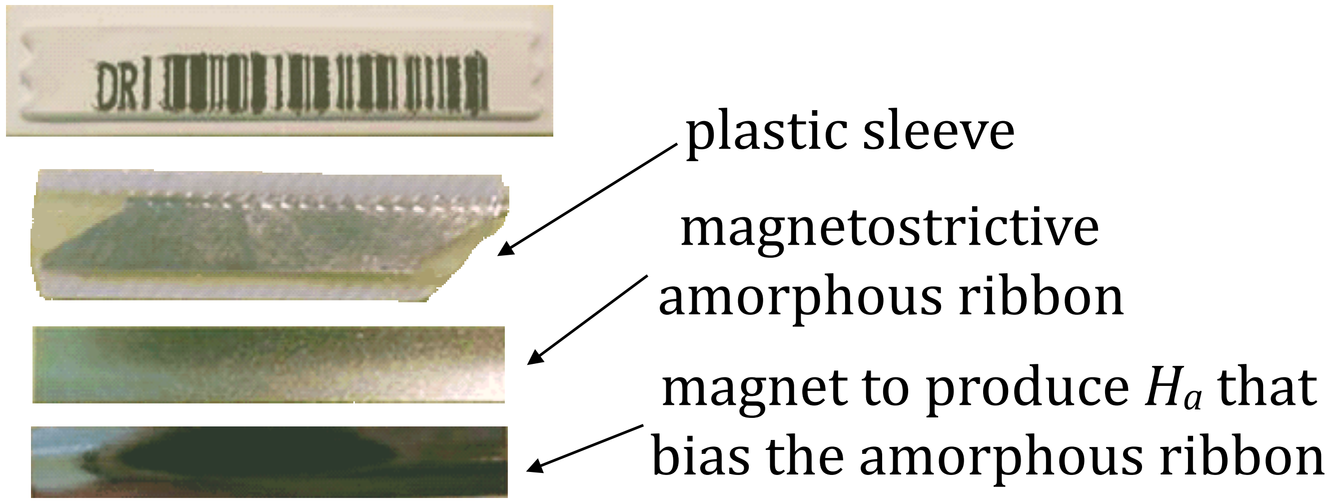


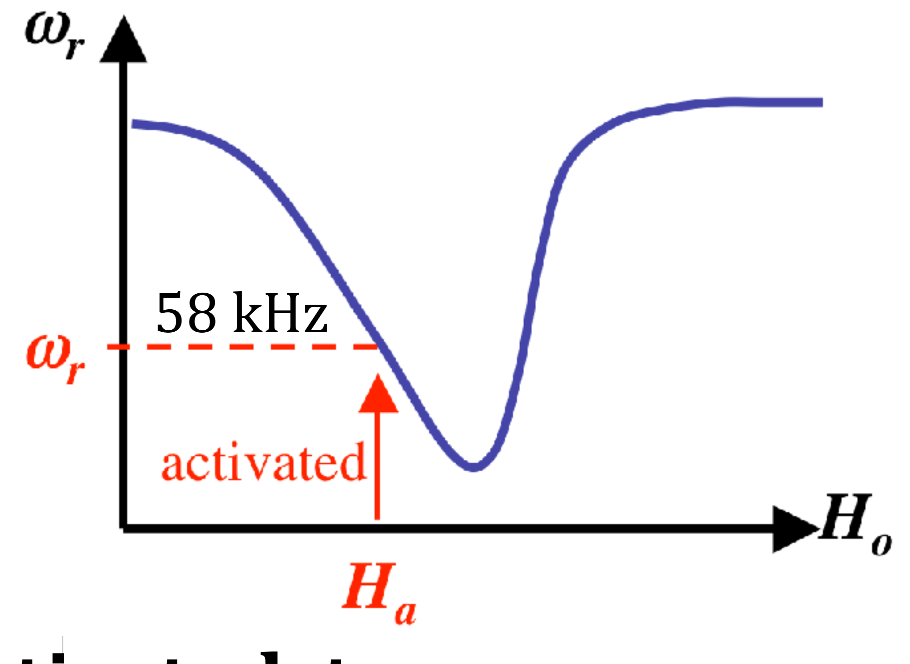
magnetoelastic resonance frequency

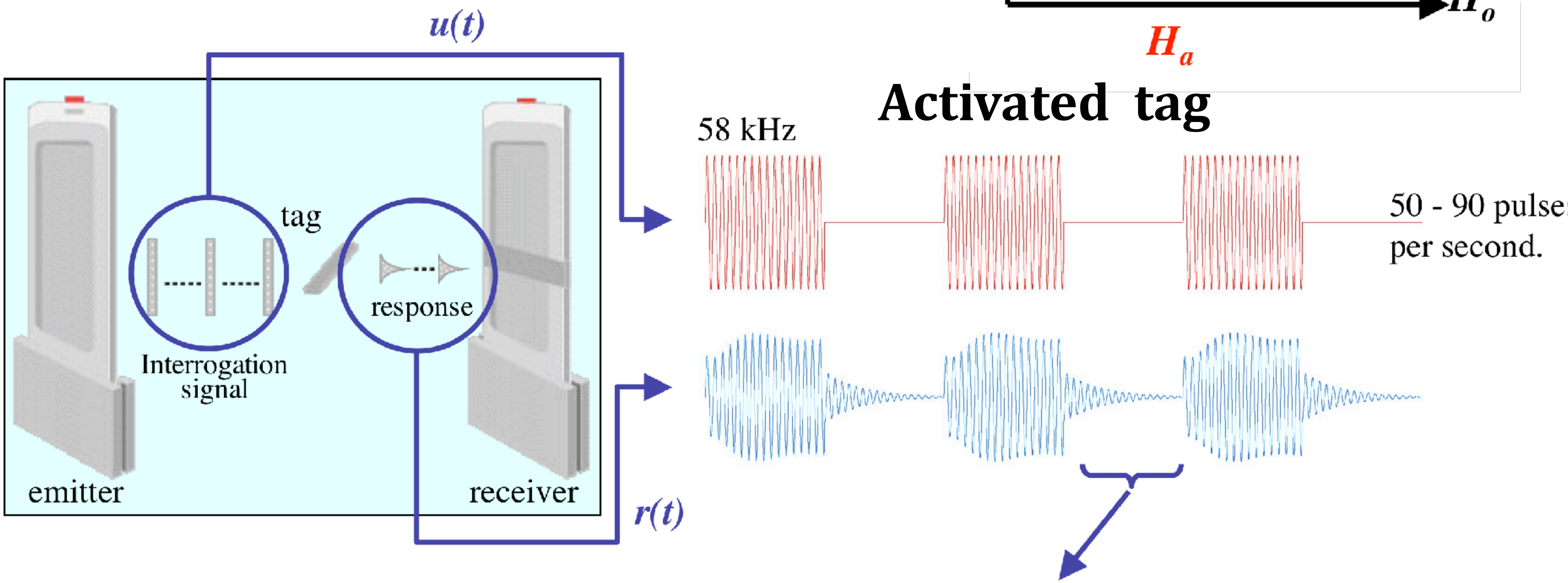
$$\omega_n = n\pi \frac{\sqrt{E/\rho}}{l}$$

The resonance frequency can be tuned with an applied magnetic field

Sensing principles Magnetoelastic sensors



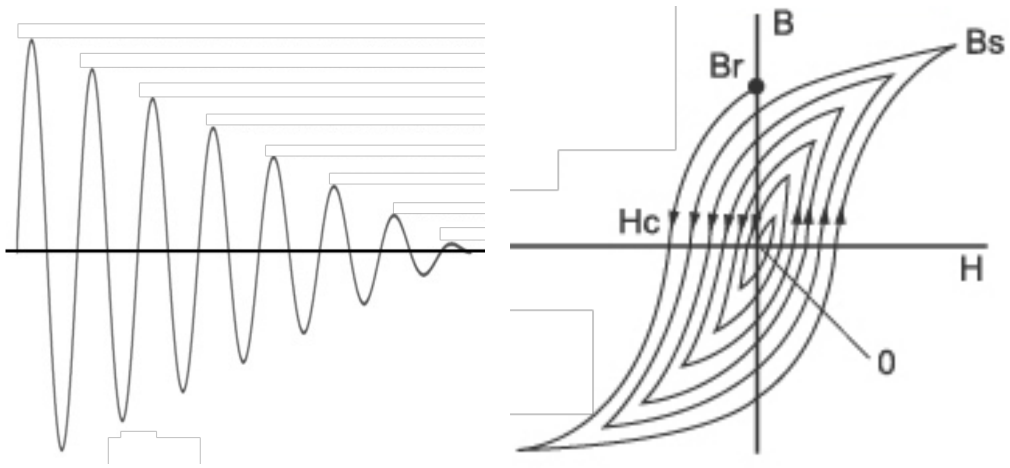


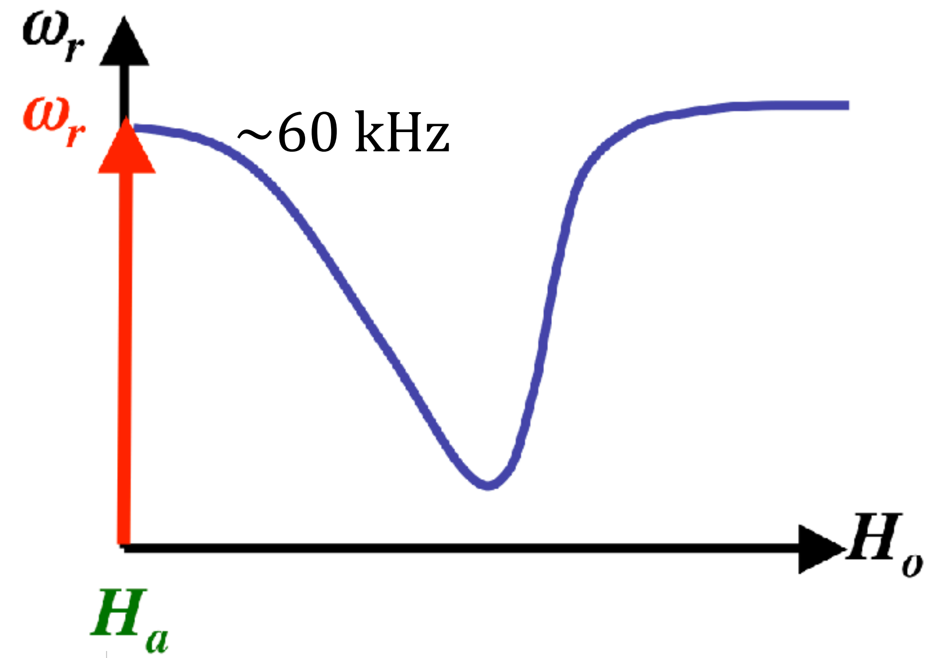


The emitter pulses **excite oscillations** that remain after the pulses end if the element is tuned to the pulses frequency

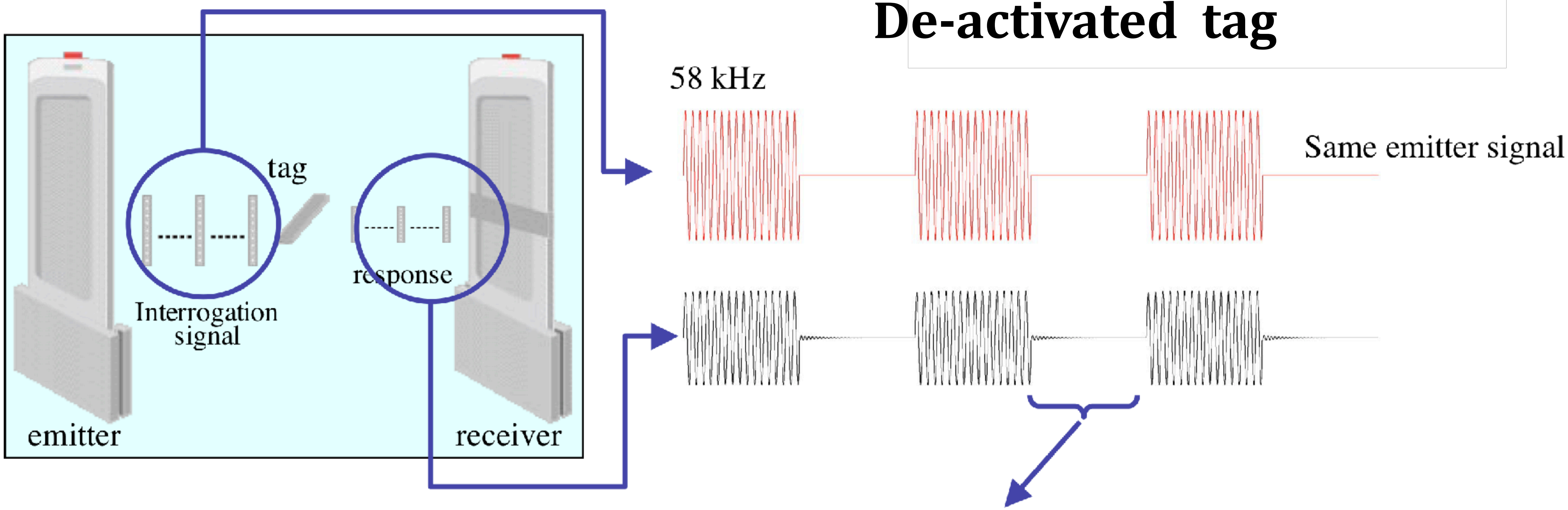
The receiver **detects oscillations between pulses**

The tag is deactivated at the counter by demagnetizing the magnet.





De-activated tag



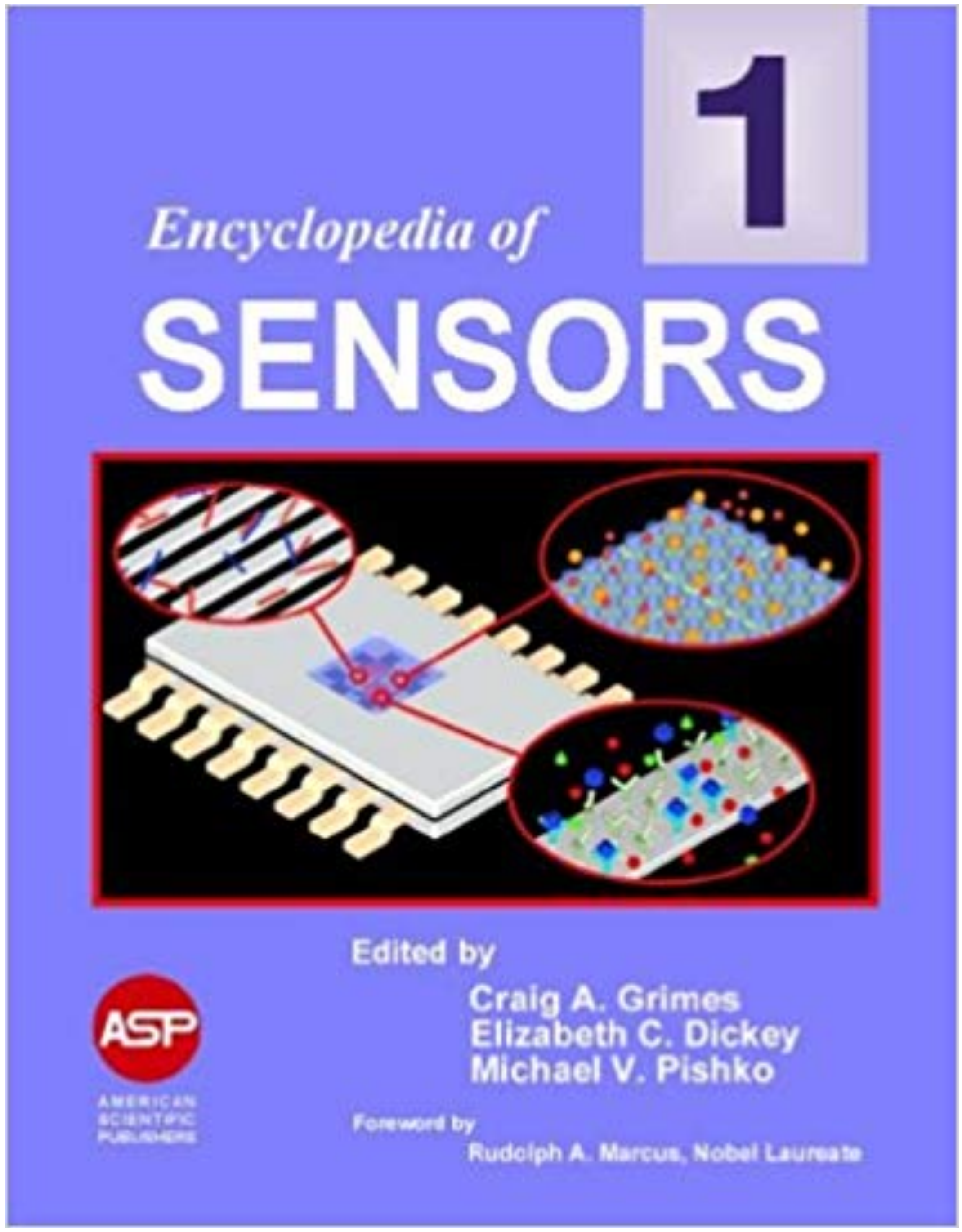
Oscillations decay shortly after the pulse end for the un-tuned element

The receiver **do not detect oscillations between pulses**

Magnetoelastic sensors

More on anti-shoplifting labels in G. Herzer, *J. Magn. Magn. Mater.* **254-255** 598-602 (2003).

Many more details on magneto elastic sensors: *Encyclopedia of Sensors, Volume 5.*



Magnetoelastic Sensors

A. García-Arribas*, J. M. Barandiarán, and J. Gutiérrez

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Summary

Magnetic sensors detects primarily magnetic fields, but also magnitudes of other different types, using magnetic phenomena.

We have surveyed some well-stablished technologies and presented successful devices based on them:

- Inductive (presence by reluctance and eddy current sensors, position by LVDT, geomagnetism by fluxgate,…)
- Squid (magnetometry, magneto-encephalography, …)
- Hall (magnetic compasses, current sensors, encoders, …)
- Magnetoresistances (read-heads, MRAM, …)
- Magnetoelastic sensors (torque, anti-shoplifting labels, …)

There are many other types of magnetic sensors and technologies.
P. Ripka, *Magnetic Sensors and Magnetometers*, 2001, Artech House, ISBN1580530575.

New, emerging technologies, promises exciting new developments (spintronics, vortex and skyrmions, …)